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U.S. COURT OF FEDERAL CLAIMS

IN THE UNITED STATES COURT OF FEDERAL CLAIMS
508 PATENT

ROSS-HIME DESIGNS, INC. **Plaintiff,** **v.** **THE UNITED STATES AS REPRESENTED BY THE ADMINISTRATOR OF THE NATIONAL AERONAUTICS SPACE ADMINISTRATION,** **Defendant.**	**No.** **VERIFIED COMPLAINT** **11-201 C**

Plaintiff Ross-Hime Designs ("RHD") for its Complaint against Defendant National Aeronautics and Space Administration ("NASA") states and alleges as follows:

PARTIES

1. Plaintiff Ross-Hime Designs, Inc. is a Minnesota Domestic Corporation, which has the registered address of 1313 5th Street SE, Minneapolis, Minnesota 55414. Plaintiff specializes in the design and prototyping of humanoid robotic systems.

2. Upon information and belief, Defendant NASA is a Government Agency. Its headquarters are located in Washington, D.C. 20546.

JURISDICTION AND VENUE

3. RHD alleges that this action arose because inventions described in and covered in the '580 and '962 Patents are being and have been made and/or used by or for NASA without a license from Plaintiff or lawful right to use the same. Thus, this Court has jurisdiction over this action pursuant to 28 U.S.C. § 1498.

BACKGROUND ALLEGATIONS

4. This action specifically involves patents held by RHD related to robotic manipulators.

5. On October 19, 1999, United States Patent No. 5,967,580 ("580 Patent") was duly and legally issued in the name of the inventor, Mark E. Rosheim entitled "ROBOTIC MANIPULATOR". RHD is the assignee of the '580 Patent. A true and correct copy of the'580 Patent is attached as Exhibit 1 to the Complaint.

6. On December 3, 2003, United States Patent No. 6,658,962 ("962 Patent") was duly and legally issued in the name of the inventor, Mark E. Rosheim, entitled "ROBOTIC MANIPULATOR". RHD is the assignee of the '962 Patent. A true and correct copy of the '962 Patent is attached as Exhibit 2 to the Complaint.

7. Upon information and belief, NASA uses and/or makes a robotic manipulator. NASA has developed robotic manipulators identified as Robonaut 1. The Robonaut 1 includes a pair of robotic hands. NASA has developed robotic manipulators identified as Robonaut 2. The Robonaut 2 includes a pair of robotic hands.

8. A version of the robotic hand of the Robonaut 1 is shown in the photograph, a true and correct copy of which is attached hereto as Exhibit 3. The current configuration of the Robonaut 1 robotic hand includes all of the structural features that are labeled and shown in Exhibit 3. The current configuration of the Robonaut 1 robotic hand includes a palm based cabled actuator. The current configuration of the Robonaut 1 robotic hand includes pitch and yaw lower knuckles and wrist pitch and yaw pivots.

9. A version of the robotic hand of the Robonaut 1 is shown in the photograph, a true and correct copy of which is attached hereto as Exhibit 4. The current configuration of the

Robonaut 1 robotic hand includes all of the structural features that are labeled and shown in Exhibit 4. The current configuration of the Robonaut 1 robotic hand includes lower knuckle cabled actuators, thumb knuckles and finger bases.

10. A version of the robotic hand of the Robonaut 1 is shown in the photograph, a true and correct copy of which is attached hereto as Exhibit 5. The current configuration of the Robonaut 1 robotic hand includes all of the structural features that are labeled and shown in Exhibit 5. The current configuration of the Robonaut 1 robotic hand includes a thumb cabled actuator, lower thumb knuckle and palm.

11. The current configuration of Robonaut 1 robotic hand includes actuators for each of the segments of the fingers and palm.

12. A version of the robotic hand of the Robonaut 2 is shown in the NASA slideshow CAD drawing, a true and correct copy of which is attached hereto as Exhibit 6. The dotted red lines in Exhibit 6 depict lower knuckle cabled actuators. The current configuration of the Robonaut 2 robotic hand includes all of the structural features that are labeled and shown in Exhibit 6. The current configuration of the Robonaut 2 robotic hand includes lower knuckles and wrist pitch and yaw pivots.

13. A version of the robotic hand of the Robonaut 2 is shown in the NASA slideshow CAD drawing, a true and correct copy of which is attached hereto as Exhibit 7. The lower thumb knuckle in Exhibit 7 is connected to thumb cabled actuators. The current configuration of the Robonaut 2 robotic hand includes all of the structural features that are labeled and shown in Exhibit 7. The current configuration of the Robonaut 2 robotic hand includes finger and thumb knuckles, a wrist pitch and yaw pivots, wrist rod actuators, a pitch and yaw thumb knuckle.

14. A version of the robotic hand of the Robonaut 2 is shown in the NASA slideshow photograph, a true and correct copy of which is attached hereto as Exhibit 8. The current configuration of the Robonaut 2 robotic hand includes all of the structural features that are labeled and shown in Exhibit 8. The current configuration of the Robonaut 2 robotic hand includes pairs of cabled actuators, thumb knuckle, upper, middle and lower finger sections, finger bases, lower knuckle and wrist rod actuator.

15. The current configuration of Robonaut 2 robotic hand includes a pair of cabled actuators for the lower finger sections.

16. Upon information and belief, NASA was aware of the '580 Patent prior to the commencement of this action.

17. Upon information and belief, NASA was aware that one or more of the claims of the '580 Patent covered Robonaut 1.

18. Upon information and belief, NASA was aware of the '962 Patent prior to the commencement of this action.

19. Upon information and belief, NASA was aware that one or more of the claims of the '962 Patent covered Robonaut 2.

COUNT I-INFRINGEMENT OF '580 PATENT

20. Plaintiff hereby realleges and incorporates all preceding paragraphs.

21. Upon information and belief, NASA has caused and continues to cause the making and/or the use of that of which is described in and covered by the '580 Patent, without license or other lawful right. That making and/or use has been and continues to be by or for NASA.

22. Upon information and belief, NASA has and continues to infringe the '580 Patent.

23. The exact amount of reasonable and entire compensation due RHD from NASA for use of the invention described in and claimed by the '580 Patent is not currently known by RHD, and cannot be stated definitively until RHD has been provided with the necessary data in the possession of NASA, but upon information and belief, is no less than $2.5 million.

COUNT II-INFRINGEMENT OF '962 PATENT

24. Plaintiff hereby realleges and incorporates all preceding paragraphs.

25. Upon information and belief, NASA has caused and continues to cause the making and/or the use of that of which is described in and covered by the '962 Patent, without license or other lawful right. That making and/or use has been and continues to be by or for NASA.

26. Upon information and belief, NASA has and continues to infringe the '962 Patent.

27. The exact amount of reasonable and entire compensation due RHD from NASA for use of the invention described in and claimed by the '962 Patent is not currently known by RHD, and cannot be stated definitively until RHD has been provided with the necessary data in the possession of NASA, but upon information and belief, is no less than $2.5 million.

PRAYER FOR RELIEF

WHEREFORE, Plaintiff prays for judgment that:

A. U.S. Patent No. 5,967,580 is valid and the inventions claimed therein have been made and/or used by NASA without license or lawful right;

B. U.S. Patent No. 6,658,962 is valid and the inventions claimed therein have been made and/or used by NASA without license or lawful right;

C. Plaintiff be awarded the reasonable and entire compensation for use of the inventions claimed in the '580 and '962 Patents in an amount that is not less than $2.5 million;

D. Plaintiff be awarded reasonable costs in this suit, including reasonable attorney's fees;

E. Plaintiff be awarded such other and further relief as it may be entitled under the applicable United States Statute; and

F. Plaintiff be awarded such other and further relief as this Court may deem just and proper.

DEMAND FOR JURY TRIAL

Pursuant to Rule 38 of the Federal Rules of Civil Procedure, Plaintiff hereby demands a trial by jury on all the issues so triable.

RIMAS LAW FIRM, PLLC

Dated: March 30, 2011

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ATTORNEY FOR PLAINTIFF
ROSS-HIME DESIGNS, INC.

VERIFICATION

I have reviewed the foregoing Complaint and declare under penalty of perjury that the facts stated therein are true and correct to the best of my knowledge. Executed in Deephaven, Minnesota on March 30, 2011.

Mark Rosheim, President
Ross-Hime Designs, Inc.

US005967580A

United States Patent [19]

Rosheim

[11] **Patent Number:** **5,967,580**

[45] **Date of Patent:** ***Oct. 19, 1999**

[54] **ROBOTIC MANIPULATOR**

[75] Inventor: **Mark E. Rosheim**, St. Paul, Minn.

[73] Assignee: **Ross-Hine Designs, Incorporated**, St. Paul, Minn.

[*] Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

[21] Appl. No.: **08/978,192**

[22] Filed: **Nov. 25, 1997**

Related U.S. Application Data

[63] Continuation of application No. 08/525,395, Sep. 8, 1995, abandoned, which is a continuation-in-part of application No. 08/497,199, Jun. 30, 1995, abandoned.

[51] **Int. Cl.**[6] **B66C 3/16**

[52] **U.S. Cl.** **294/88**; 294/106; 414/5; 901/29; 901/37

[58] **Field of Search** 414/2, 4, 5, 729; 901/30, 31, 32, 29, 37; 623/57, 64; 294/88, 106, 111; 212/238, 261

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Primary Examiner—Donald W. Underwood
Attorney, Agent, or Firm—Kinney & Lange, P.A.

[57] **ABSTRACT**

A pair of connected joints in a master-slave robotic system each operated by a plurality of force imparting means. Such force imparting means for the second joint imparts force thereto at an acute angle. A third joint is used with a flexible drive tape partly internal thereto. A gripping system having an orthogonally rotatable base effector is supported by this joint using a pair of linear actuators to position the base effector as desired. A counterpart system having an orthogonally rotatable base follower orthogonally rotatable on a pair of linear actuators uses the actuators to null out forces occurring thereon.

15 Claims, 16 Drawing Sheets

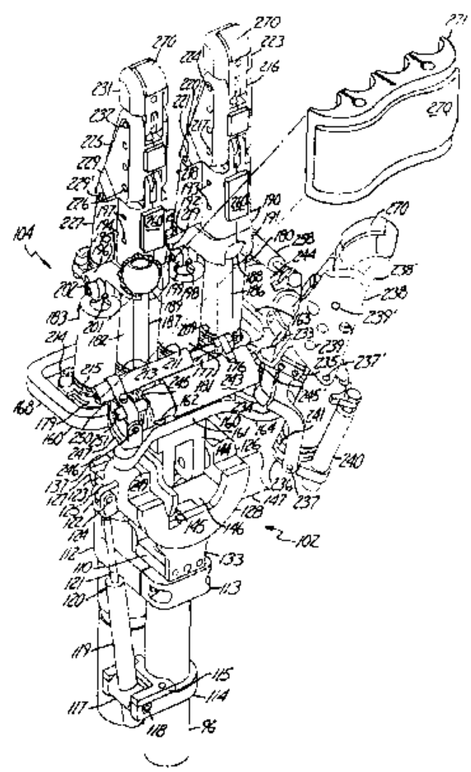

EXHIBIT 1

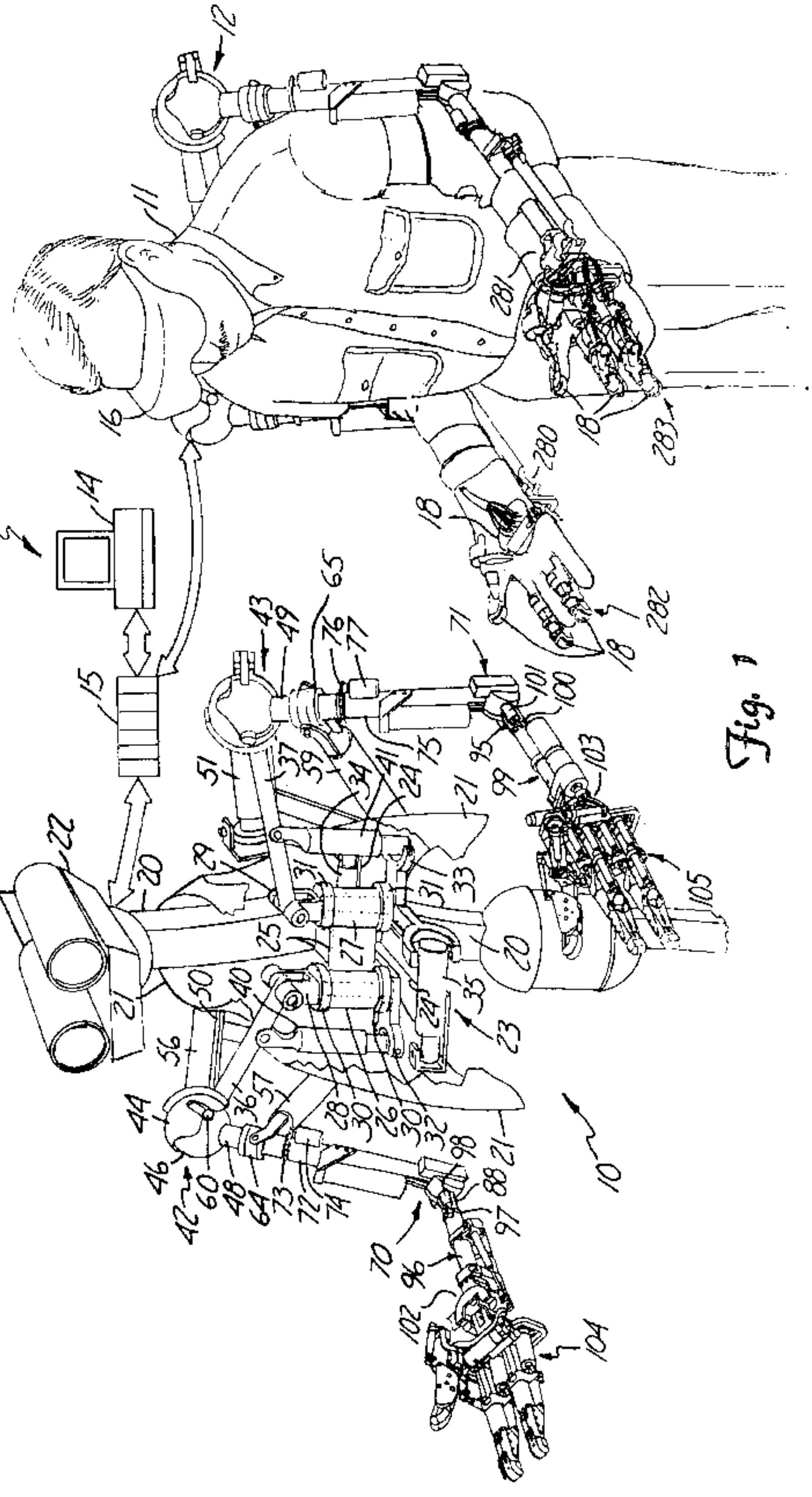

Fig. 1

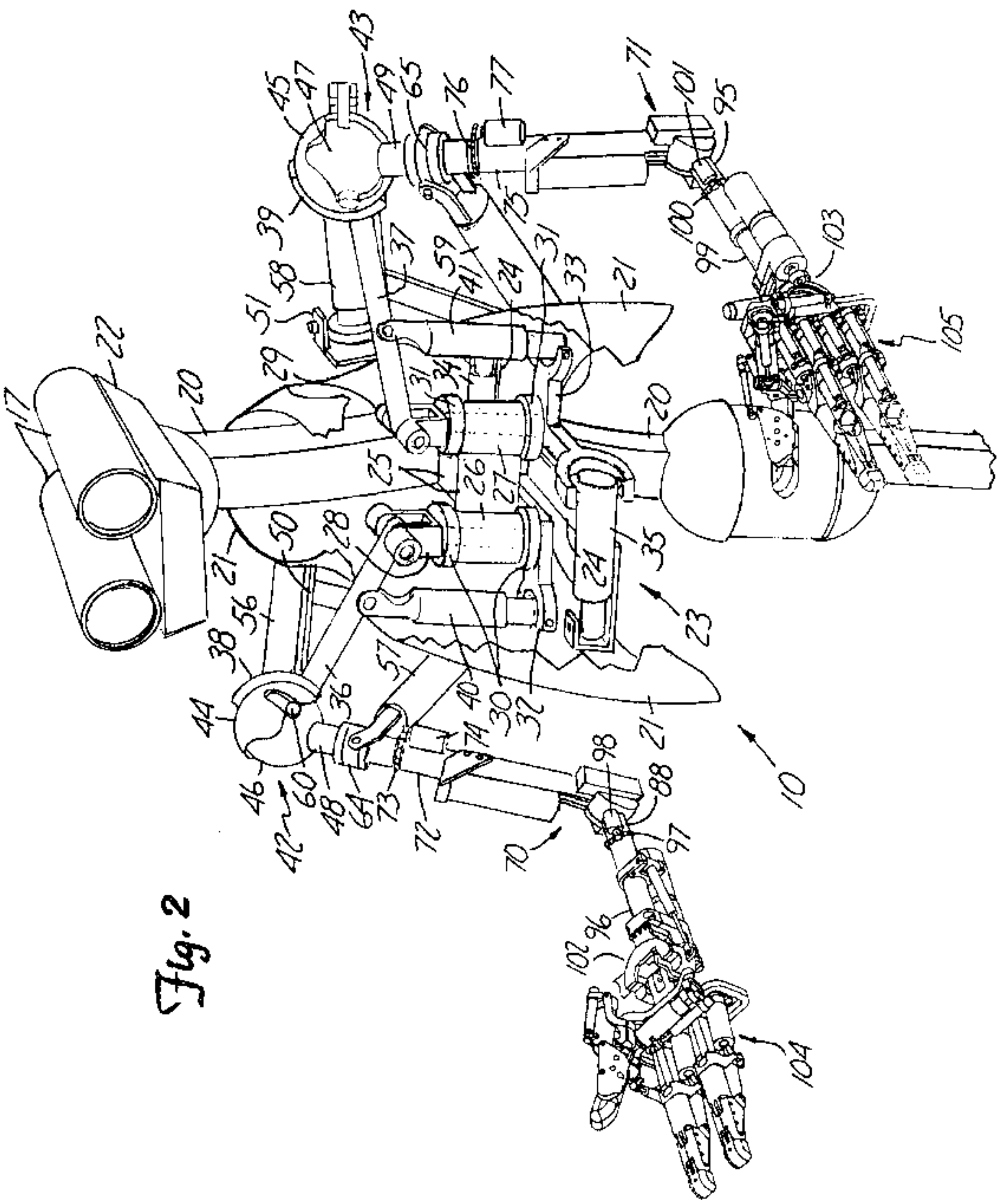
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Fig. 2

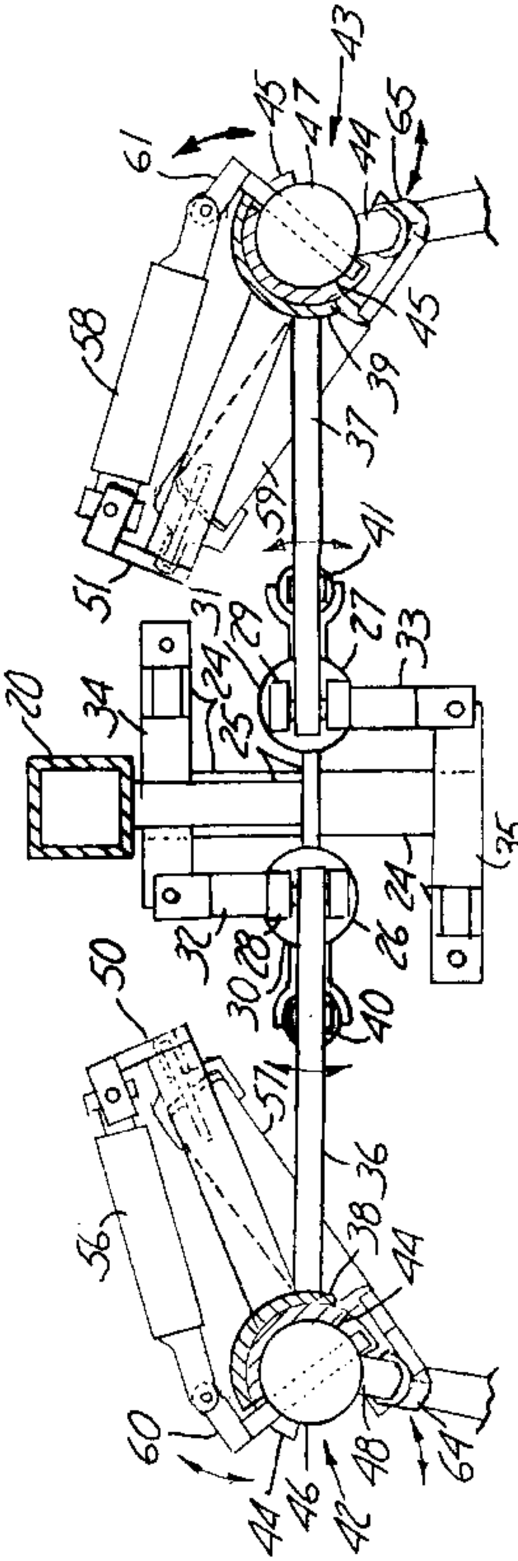


Fig.3

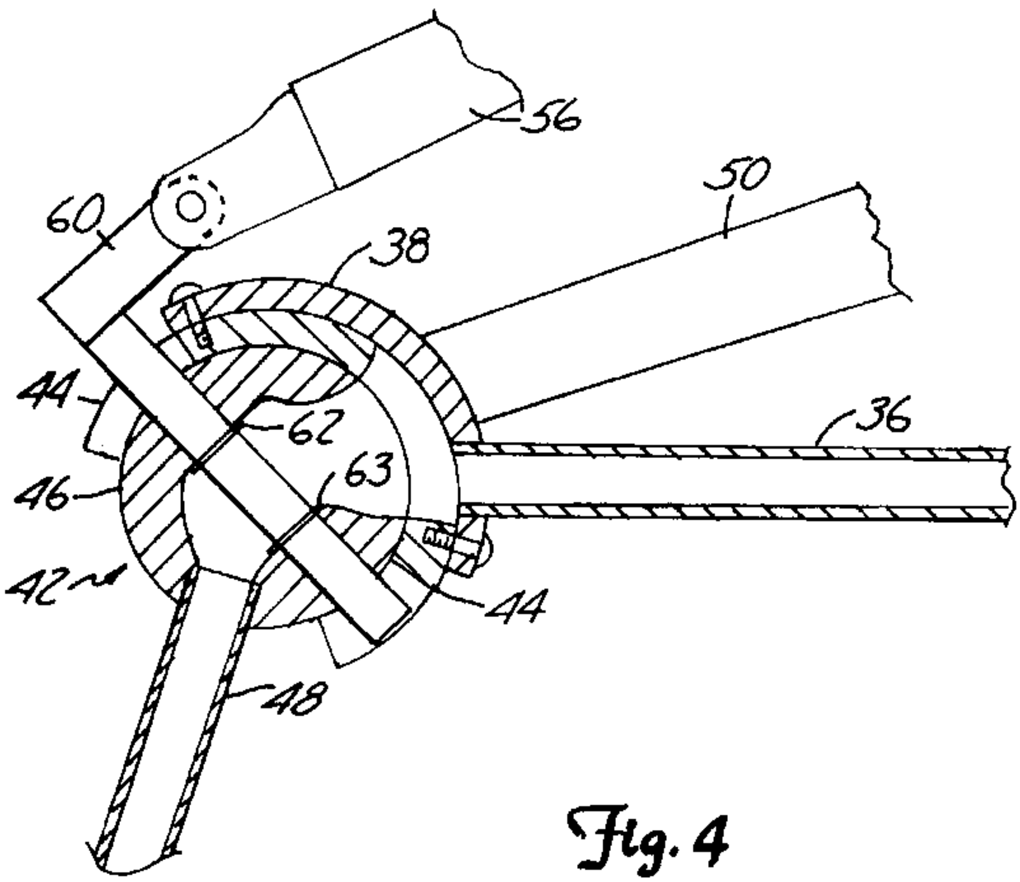


Fig. 4

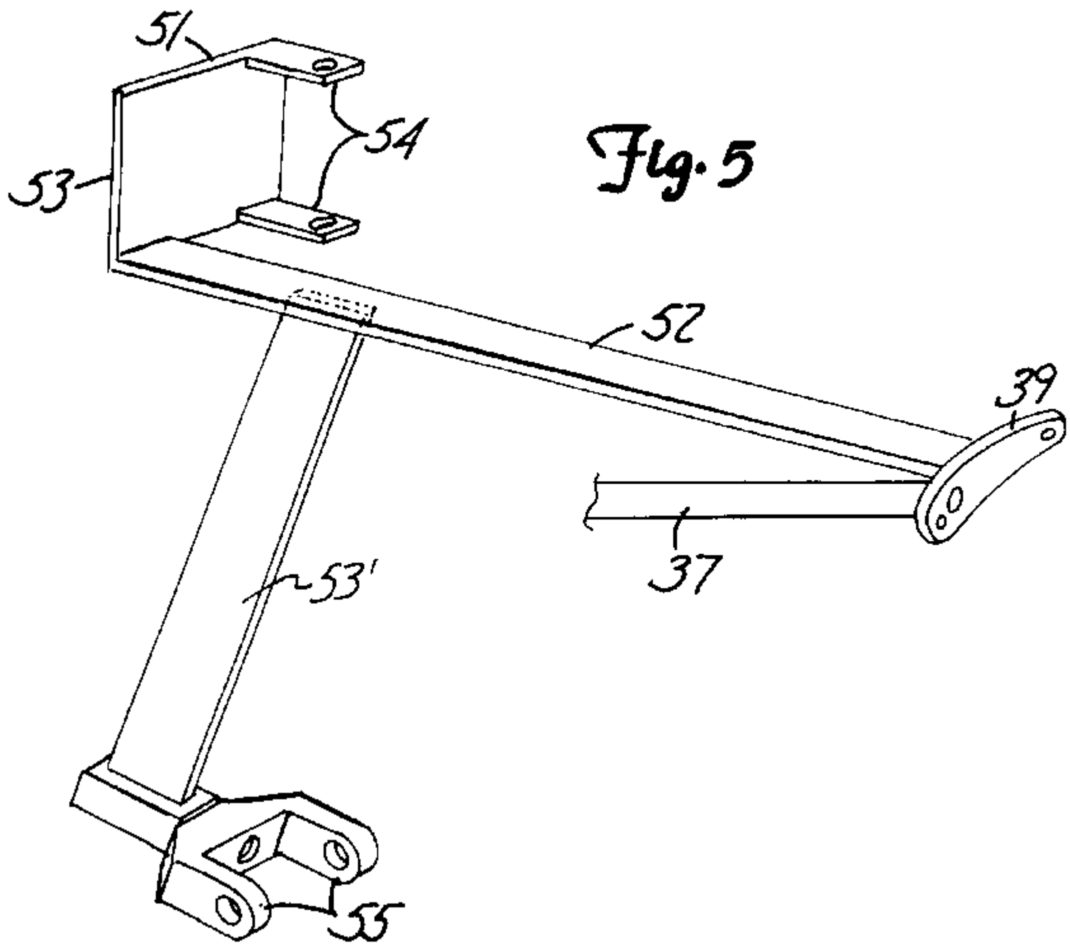


Fig. 5

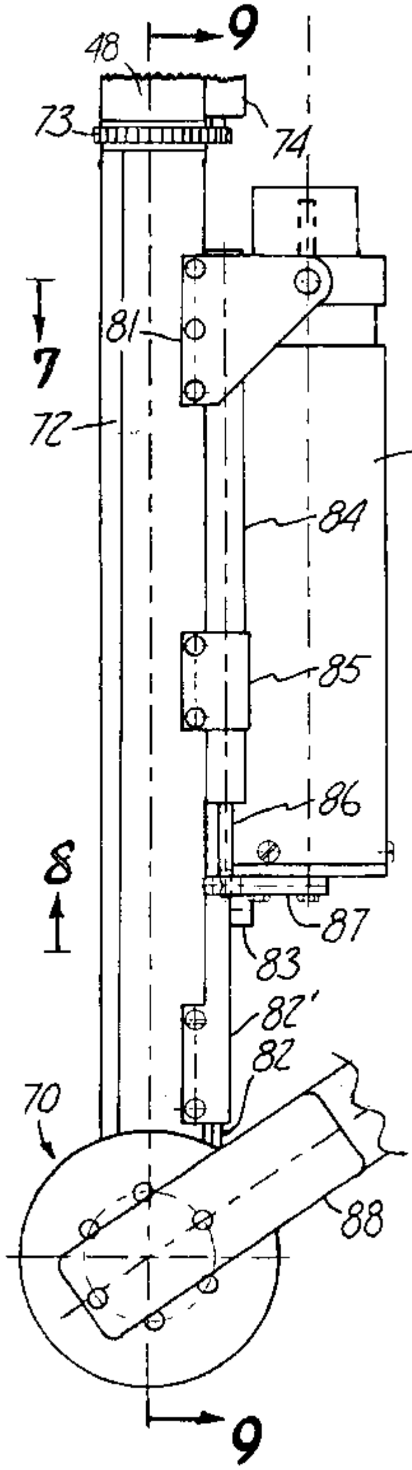


Fig. 6

Fig. 8

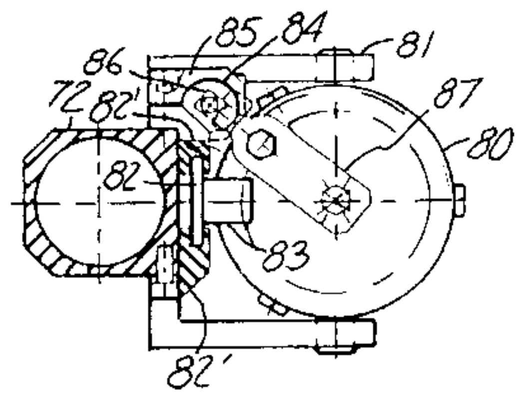
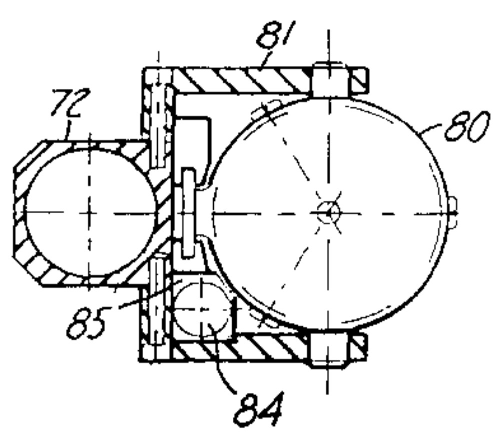


Fig. 7



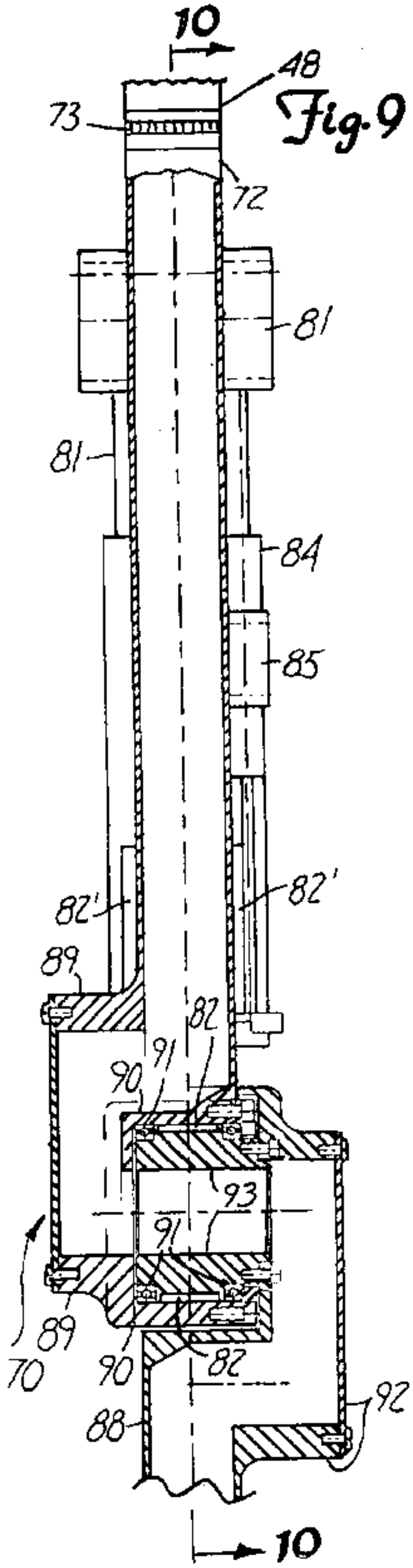

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Fig. 9

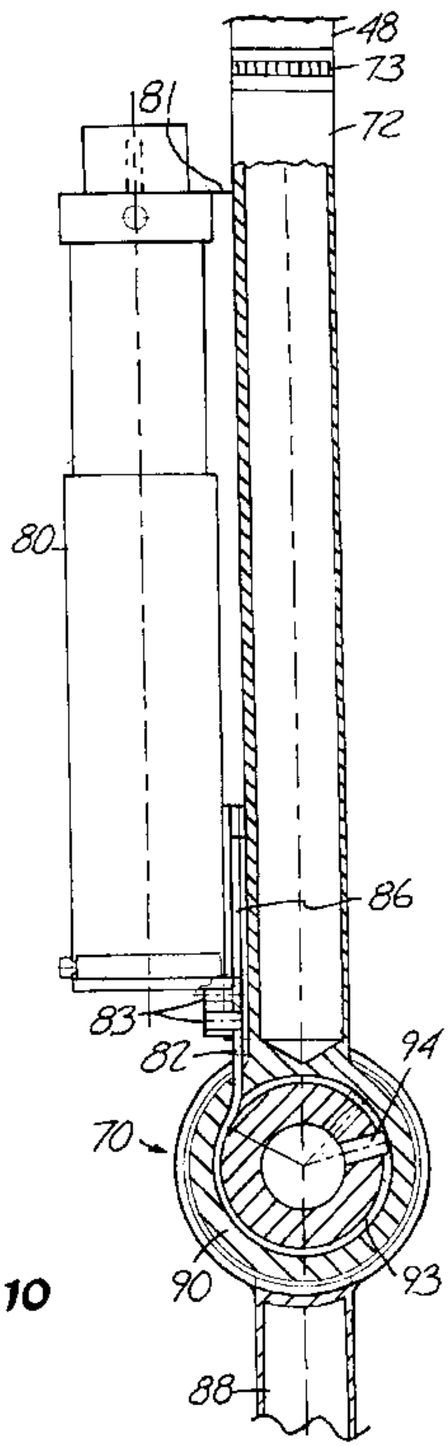
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Fig. 10

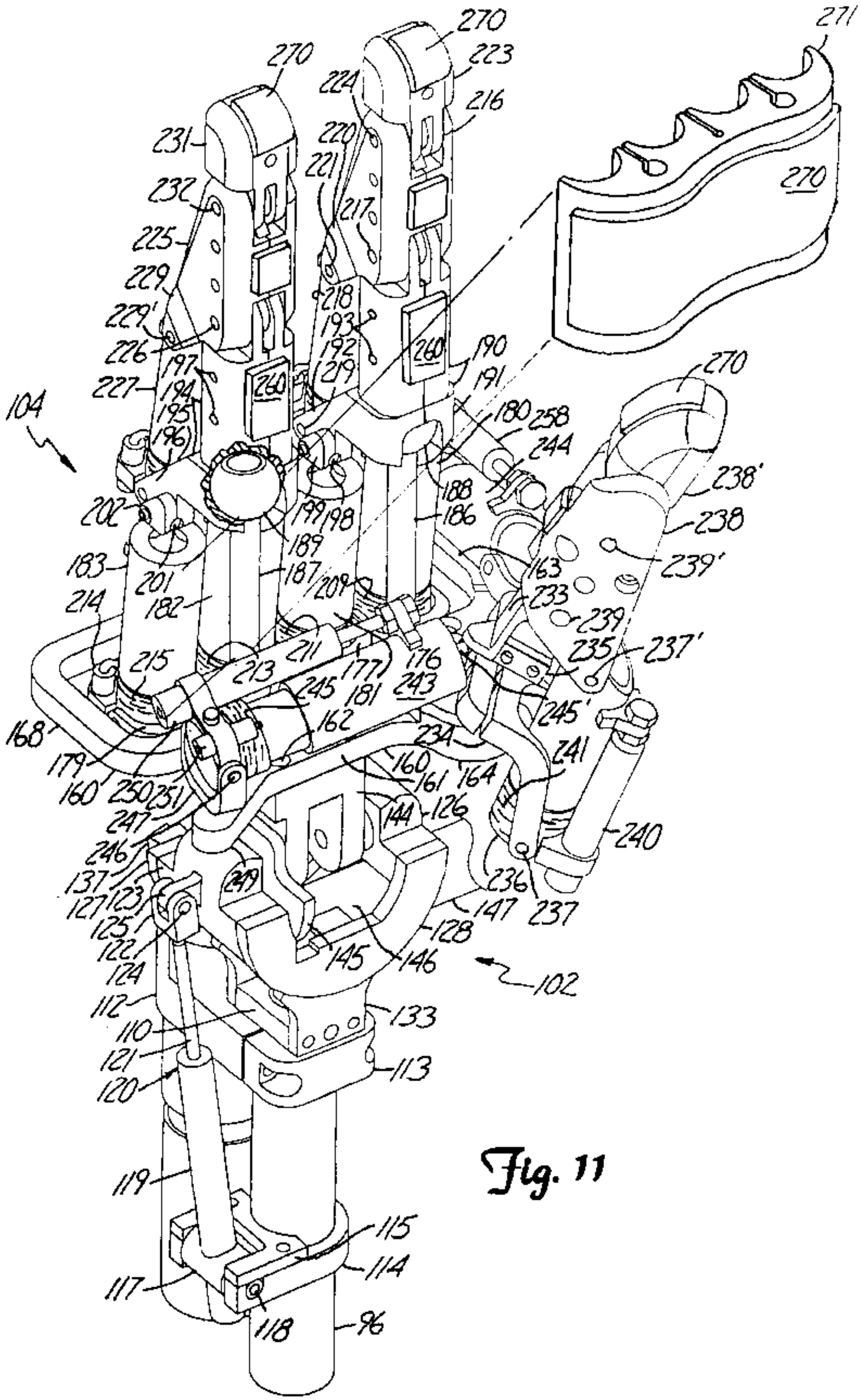
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Fig. 11

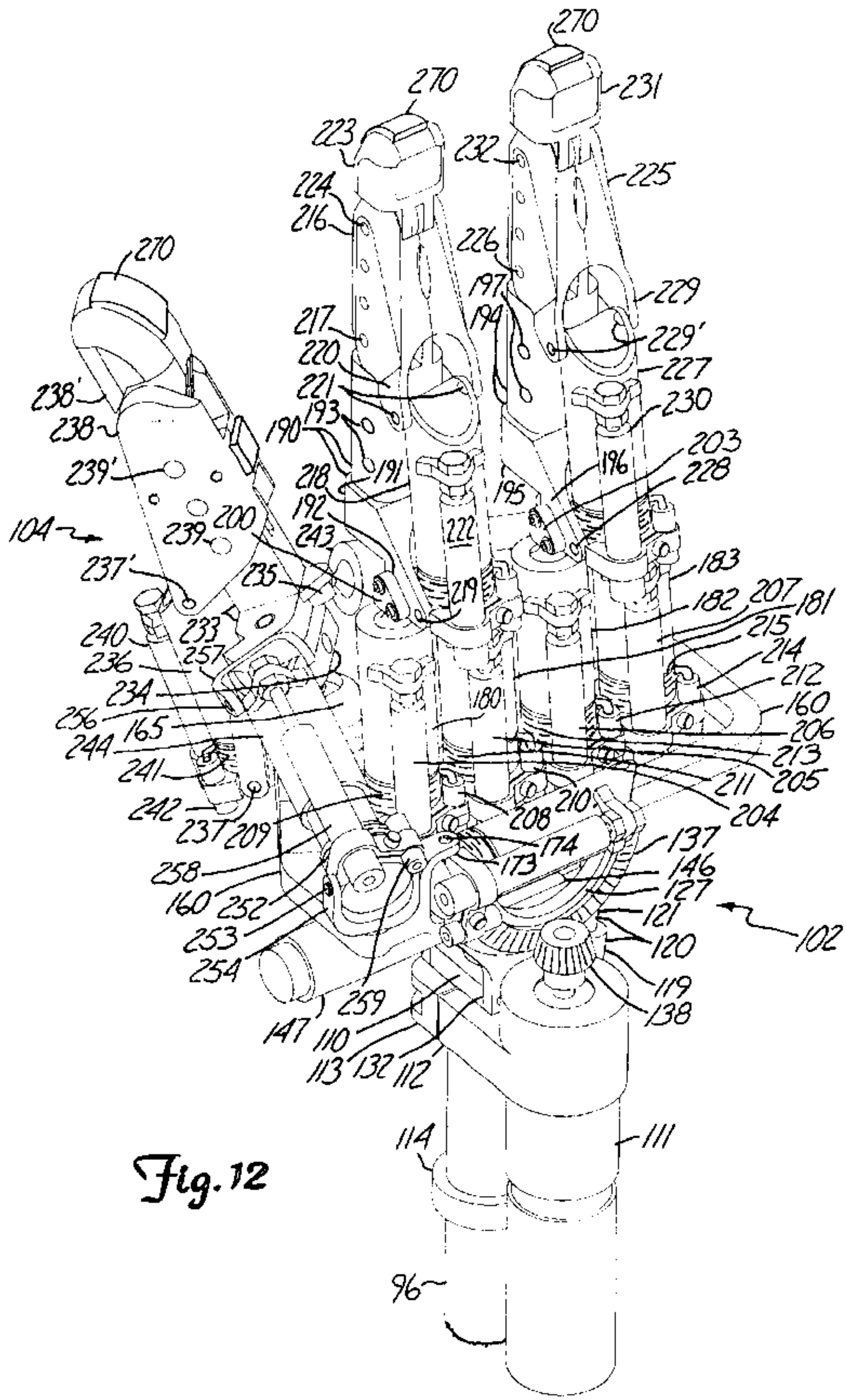
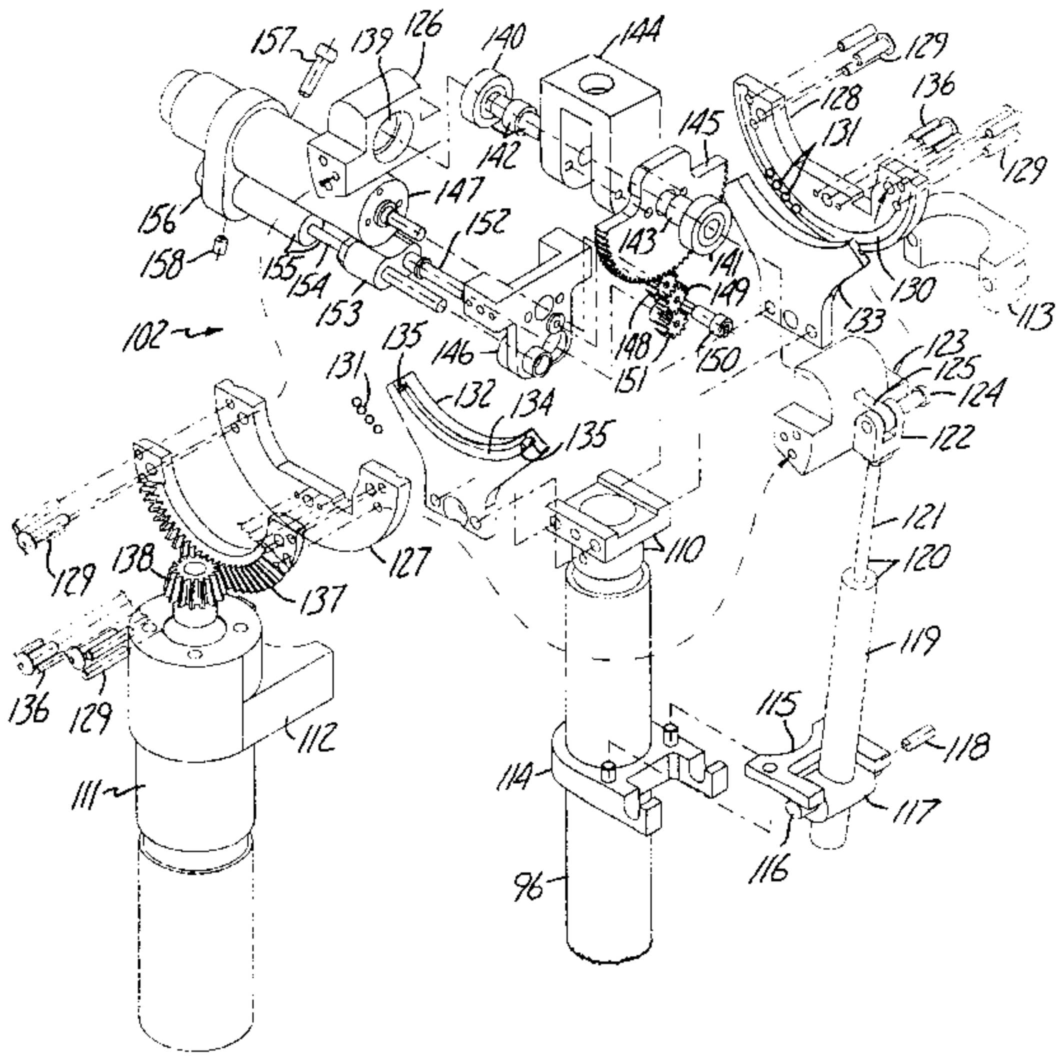


Fig. 12

Fig. 13



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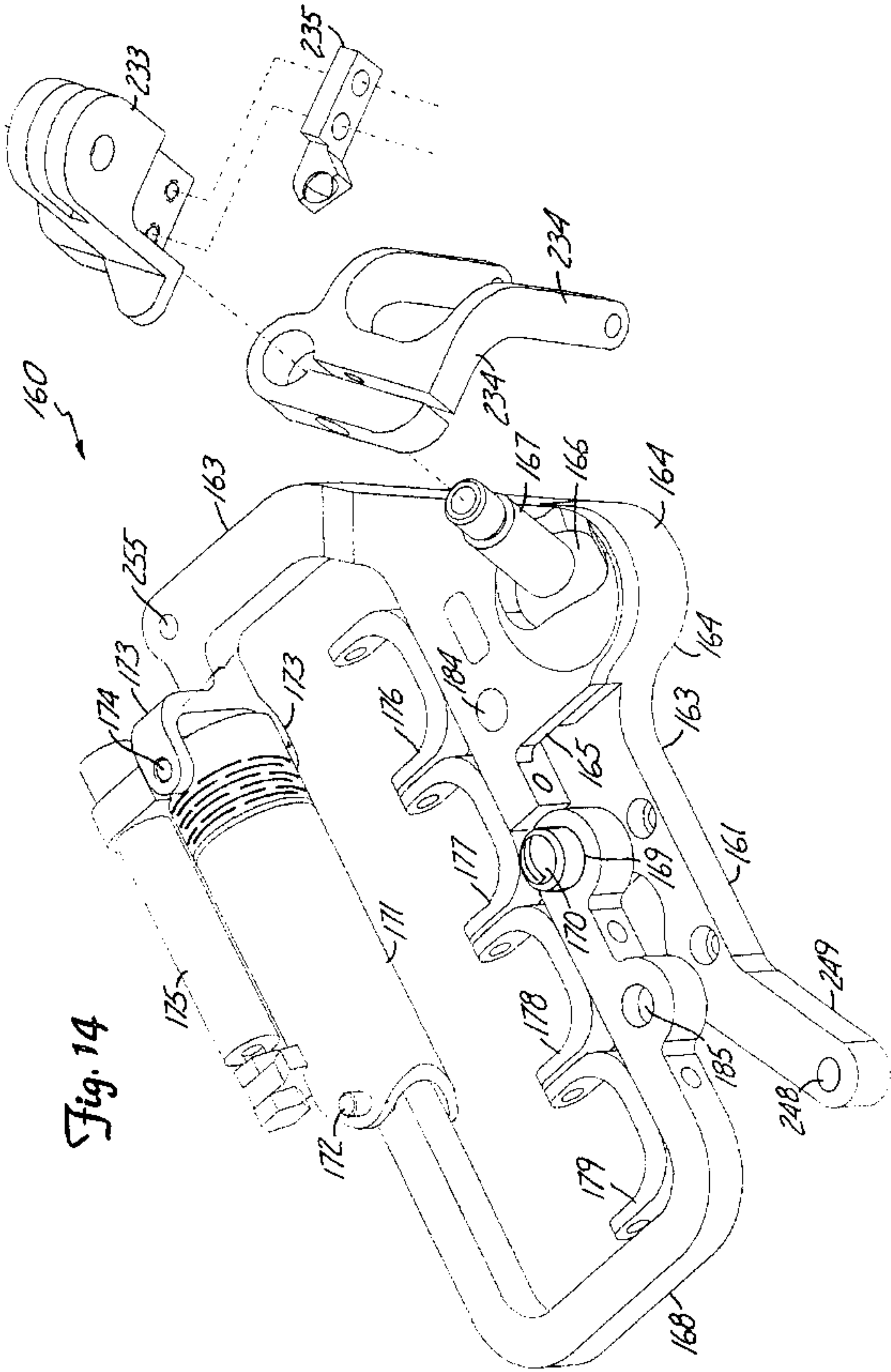

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Fig. 14

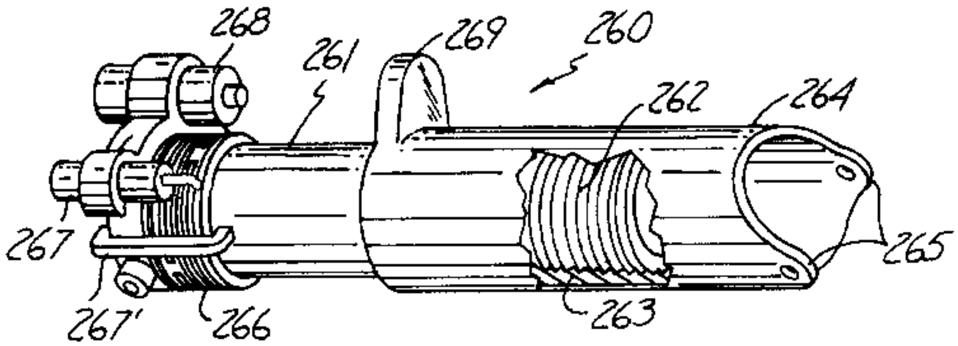
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Fig. 15

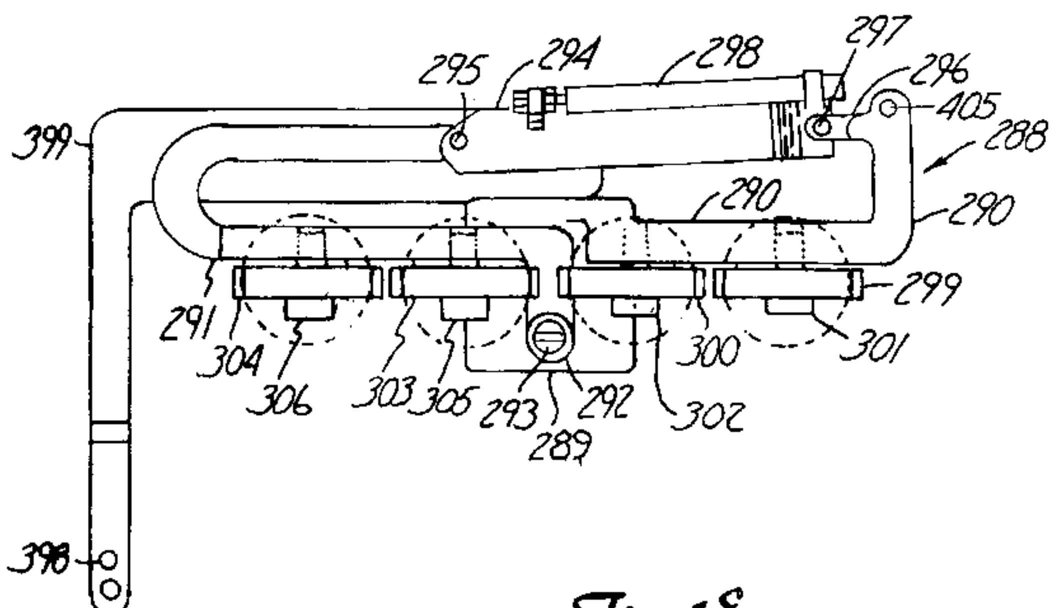
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Fig. 18

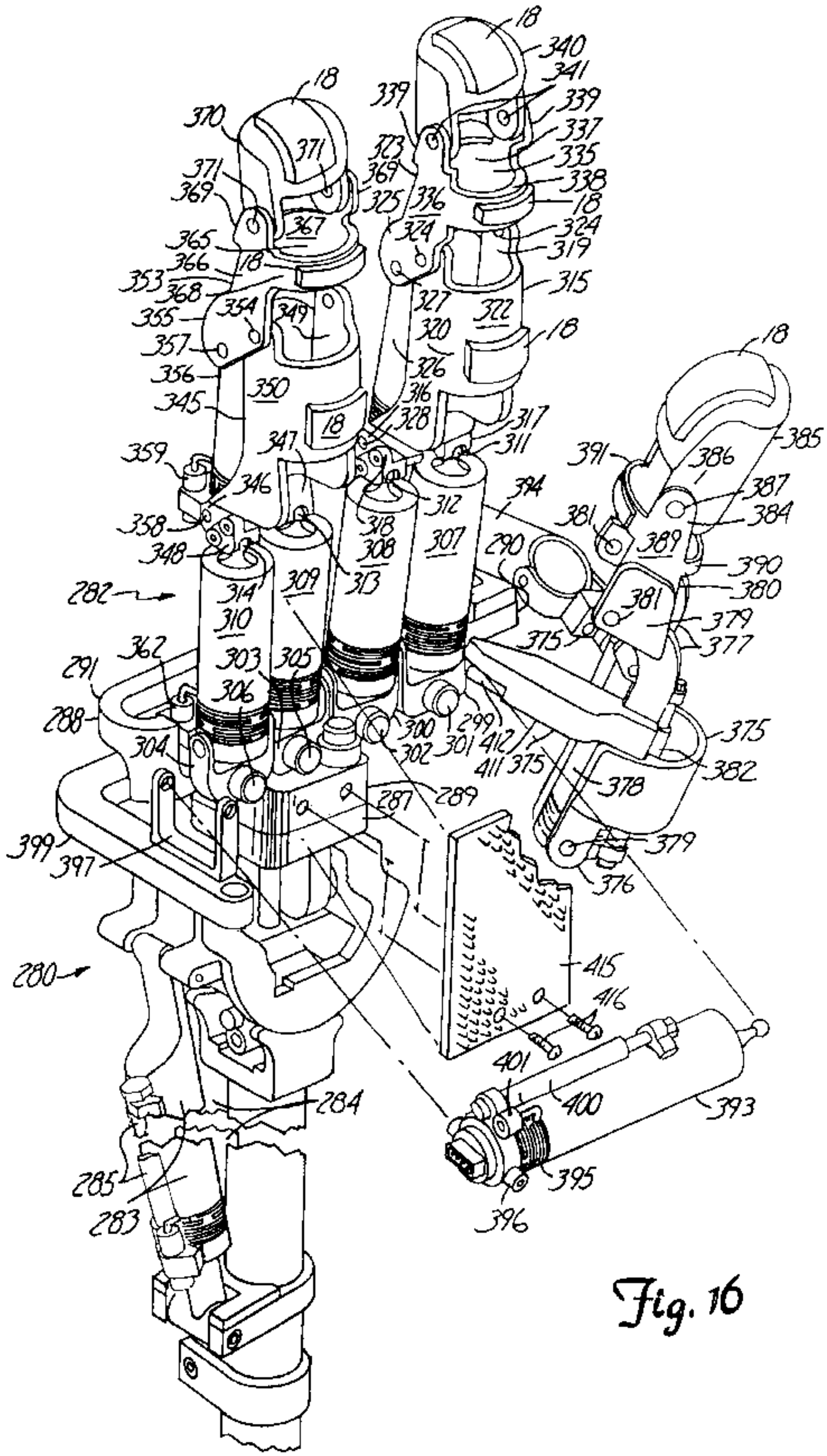


Fig. 16

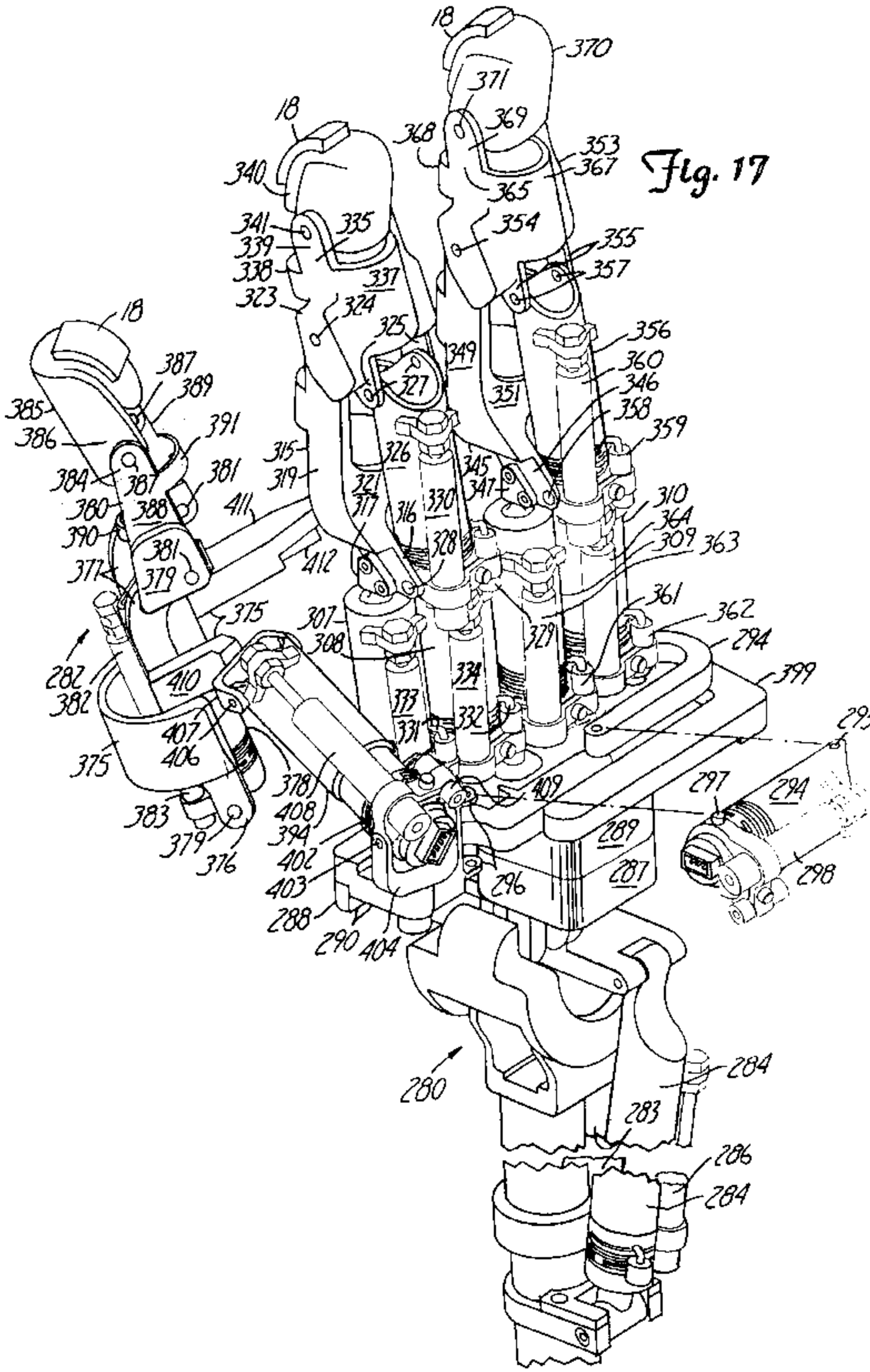
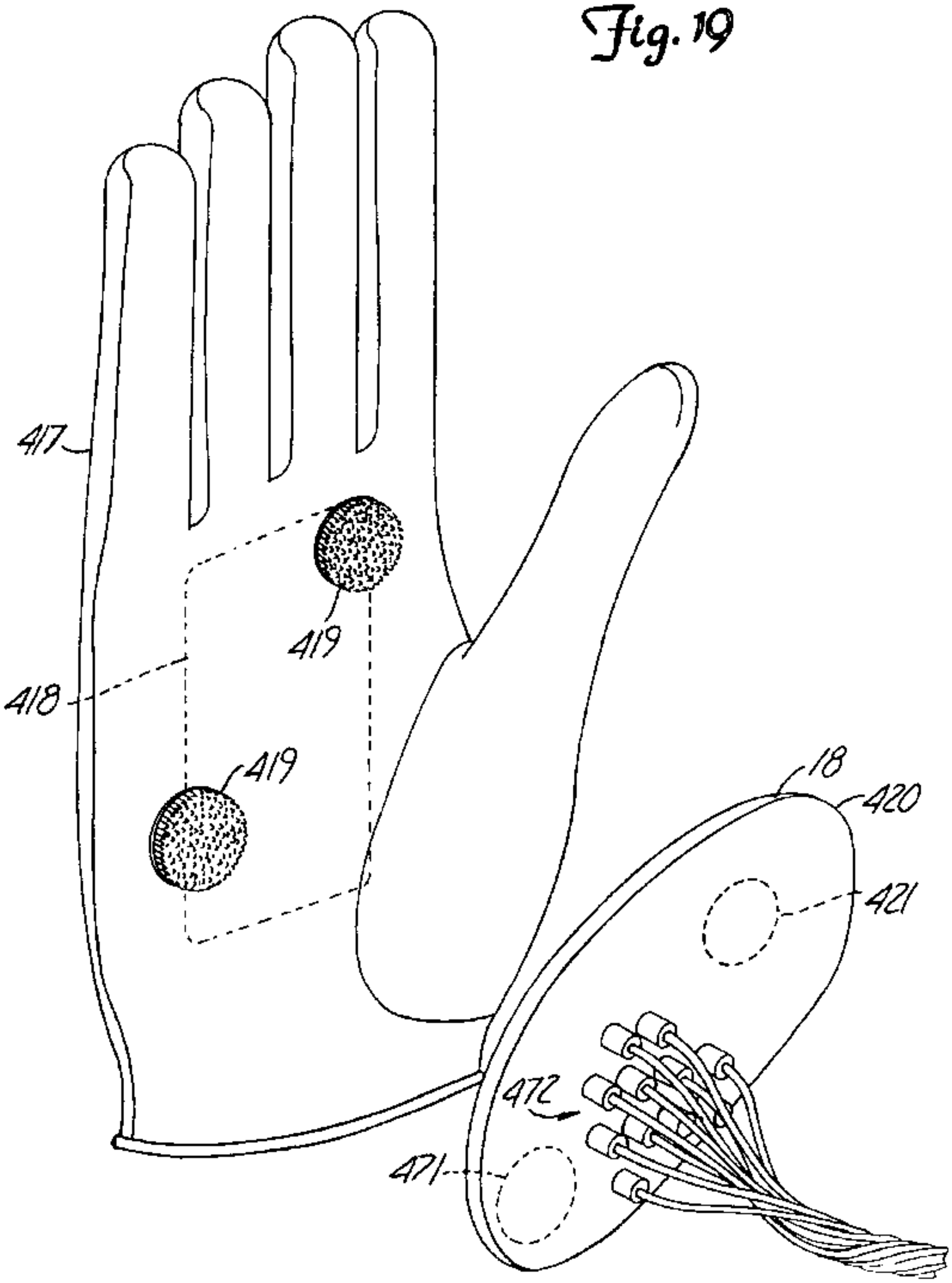


Fig. 17

Fig. 19



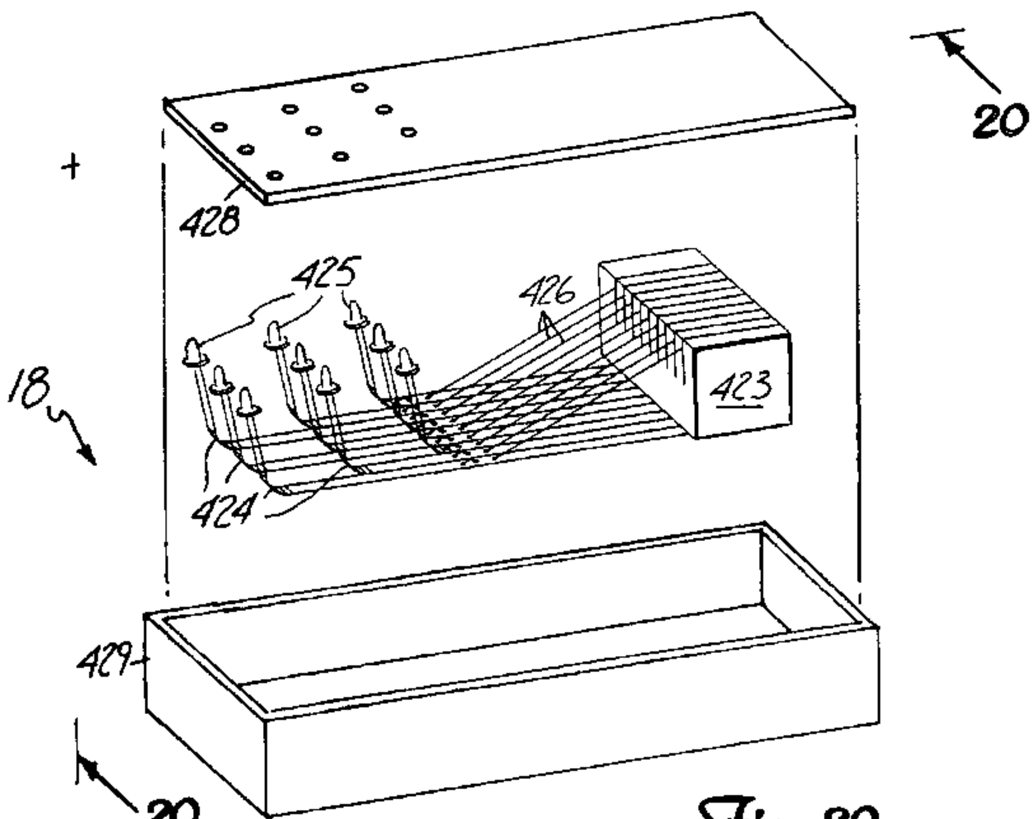


Fig. 20

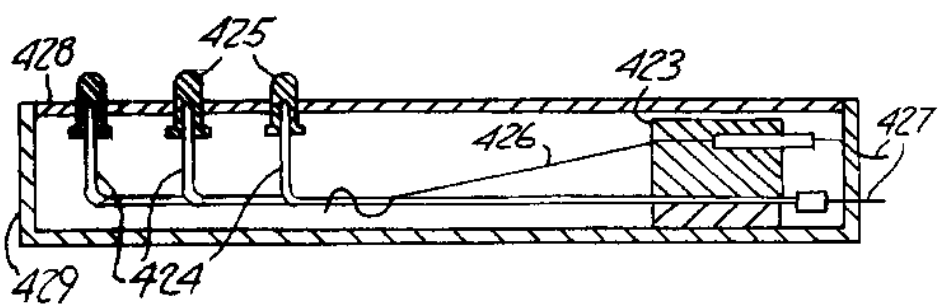


Fig. 21

ROBOTIC MANIPULATOR

This is a continuation of application Ser. No. 08/525,395, filed Sep. 8, 1995, now abandoned, which is a continuation-in-part of application Ser. No. 08/497,199, filed Jun. 30, 1995 now abandoned.

BACKGROUND OF THE INVENTION

The present invention relates to controlled motion mechanical members used as a mechanical manipulator and, more particularly, to a motion controllable, anthropomorphic mechanical manipulator providing some of the capabilities of an upper human torso.

A need for increased automation in the workplace, especially in those workplace environments unsuitable for humans, and a desire to increase the use of animated figures depicting humans or other characters often in entertainment situations, has led to substantial efforts in the development of robotics. As a result, substantial advances have occurred in many aspects of robotics.

An important aspect in robotics is the controlling of mechanical manipulators, the portion of a robot used to change the position or orientation of selected objects. In may instances, such manipulators are desired to have motion capabilities similar to those of a human chest, shoulder, arm, wrist and hand, or portions thereof.

Providing a mechanical manipulator simulating such portions of the human torso presents a difficult design problem. The chest and back portions of a human supporting a shoulder blade can be considered to have two degrees-of-freedom in motion possibilities available to it, and the shoulder ball and socket joint supporting the arm can be considered to have three degrees-of-freedom in motion possibilities available to it. In addition, the elbow can be considered to have a single degree-of-freedom in its possible motion and the wrist can be considered to have three degrees-of-freedom in motion possibilities available for it. Finally, the human palm can be considered to have a degree-of-freedom in its relative motion possibilities while the fingers and thumb thereon can be considered to have four degrees-of-freedom in the motion possibilities thereof.

A number of mechanical joints or mechanical manipulators have been proposed which attempt to exhibit the motion possibilities of the corresponding human joints, and some of these proposals have actually achieved corresponding capabilities to a significant degree. These joints typically have a base on which one side of the joint is fastened, and from which a force imparting arrangement is provided to operate movable members in this fastened portion of the joint. Mechanical transmission arrangements then couple this motion on this fastened side of the joint to the controlled side of the joint to cause that portion to correspondingly move.

However, such joints have often been constructed using a substantial number of parts causing significant expense, and with the result that they are often difficult to assemble. Further, such joints often fail to have the controlled portion thereof exhibit the desired dexterity and range of motion. In addition, the construction have often exhibited bulky geometries which do not appear much like those of the human counterparts. Also, control of the controlled side of the joint has often been insufficient in the operator not having convenient controlling arrangements available. Thus, there is desire to joint arrangements overcoming such deficiencies so that a human look-alike upper torso and arm mechanical manipulator can be provided with motion possibilities substantially equivalent to that of the upper human torso and arm.

SUMMARY OF THE INVENTION

The present invention provides a pair of connected joints and force imparting means therefor especially suitable for use in anthropomorphic master-slave robotic system. The force imparting means for the second joint imparts force thereto at an acute angle with respect to the connection between the two joints. A third joint is operated by a flexible tape passing through one joint member to operate the other.

Beyond the third joint is supported a structure having a frame with an extension to which a base effector is rotatably connected to be rotatable in orthogonal directions along with a pair of linear actuators each rotatably connected to that extension on either side of where the base effector is connected and each rotatably connected to the base effector on either side of where the extension is connected thereto. A counterpart structure for controlling this first structure omits the connection between such a frame and base effector of the first structure while keeping the actuator connections to each, and provides means for engaging the controlling operator's hands.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a pictorial view of a master-slave robot and robotic control arrangement embodying the present invention;

FIG. 2 shows a pictorial view of a slave robot embodying the present invention;

FIG. 3 shows a plan view of a portion of the structure shown in FIG. 2;

FIG. 4 shows a cross section view of a portion of the structure shown in FIGS. 2 and 3;

FIG. 5 shows a pictorial view of a portion of the structure shown in FIGS. 2 and 3;

FIG. 6 shows an elevational view of a portion of the structure shown in FIG. 2;

FIG. 7 shows a cross section view of the structure shown in FIG. 6;

FIG. 8 shows a cross section view of the structure shown in FIG. 6;

FIG. 9 shows a cross section view of the structure shown in FIG. 6;

FIG. 10 shows a cross section view of the structure shown in FIG. 9;

FIG. 11 shows a pictorial view of a portion of the structure shown in FIG. 2;

FIG. 12 shows an alternative pictorial view of the structure shown in FIG. 11;

FIG. 13 shows an exploded pictorial view of a portion of the structure shown in FIGS. 11 and 12;

FIG. 14 shows a partially exploded pictorial view of a portion of the structure shown in FIGS. 11 and 12;

FIG. 15 shows a pictorial view of an alternative to a portion of the structure shown in FIGS. 11 and 12;

FIG. 16 shows a pictorial view of a portion of the structure shown in FIG. 2;

FIG. 17 shows an alternative pictorial view of the structure shown in FIG. 11;

FIG. 18 shows a pictorial view of a portion of the structure shown in FIGS. 16 and 17;

FIG. 19 shows a pictorial view of a portion of the structure shown in FIG. 2 used with the structure shown in FIGS. 16 and 17;

FIG. 20 shows a partially exploded pictorial view of a portion of the structure shown in FIGS. 16 and 17; and

FIG. **21** shows a cross section view of a portion of the structure shown in FIG. **20**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows a master-slave robot and robotic control arrangement in which a slave robot, **10**, is under the control of a human operator, **11**, through having externally mounted on the upper torso, arms and hands of that operator, a master robotic control apparatus, **12**. This control apparatus may be termed an "exoskeleton" in its being mounted about the exterior of the upper portion of that operator's body.

Control exoskeleton **12**, in being attached to the operator's upper torso, arms and hands, senses each motion of these bodily parts of the operator and transmits signals carrying such information from a transmitter therein not seen in FIG. **1**, to a control arrangement, **13**. Control arrangement **13** is operated under the direction of a computer, **14**, which controls operation of a system controller, **15**. Operator **11**, or another, can impose further control measures on the system through computer **14** such as setting system parameter values, etc. Controller **15** has a receiver therein to receive transmissions from the transmitter in control exoskeleton **12**, and has a transmitter therein to send information signals to a receiver in control exoskeleton **12** also not shown.

Similarly, controller **15** has a transmitter therein to transmit information signals to a receiver in slave robot **10**, again not separately shown but indicated to be in a portion of that robot somewhat reminiscent of a human head. This portion of slave robot **10** also has a transmitter therein for transmitting information signals to controller **15** which has a further receiver to receive same therein. Wiring arrangements are provided through the joints and joint connectors in both slave robot **10** and control exoskeleton **12** to distribute signals obtained from the receivers therein to the actuators therein intended to respond to them, and to collect signals from sensors therein to be brought to the transmitters therein.

Control exoskeleton **12**, in receiving signals from controller arrangement **13**, uses the information in those signals to operate actuators therein to aid human operator **11** in moving the exoskeleton apparatus to the extent desired by that operator. The signals received in exoskeleton **12** from control arrangement **13** are used to move the corresponding actuators therein sufficiently to null out force magnitude signals measured by force sensors thereon due to forces imposed by bodily motions of human operator **11** which force signals (and some translation magnitude signals) are transmitted to control arrangement **13**. These bodily motion based force magnitude signals (and some translation magnitude signals) are also used by control arrangement **13** to cause similar motions by similar actuators in slave robot **10** through control arrangement **13** transmitting similar signals intended for those actuators to slave robot **10**.

Such sensed signals from slave robot **10** to control arrangement **13** may include video signals subsequently transmitted by control arrangement **13** to a video display arrangement within a visor, **16**, worn by operator **11** which convey thereto the information obtained by video cameras in slave robot **10** such as those at the top thereof designated **17**. Also, the actuator signals received in control exoskeleton **12** from control arrangement **13** convey tactile force information which signals are distributed to tactile force actuators, **18**, capable of applying force to operator **11** at locations in which they are provided. These locations are in the hand-like portions of control exoskeleton **12**, both in the finger-like portions where the tactile actuators are built in and in a palm portion where the tactile actuators are provided in a glove fitted over the operators hand.

A basic motion to be simulated by slave robot **10** using the upper human torso movement simulation capability thereof is the ability of a human body to position its shoulders with respect to its rib cage and spine. That is, humans can throw their shoulders back or hunch them forward. As a basis for this simulation, slave robot **10** is provided with a human spine-like base, **20**, which is seen more clearly in FIG. **2**. The structure and actuators for simulating this motion are supported by base **20** and housed within a rib cagelike shroud, **21**, shown partly removed in FIG. **2** to avoid obscuring structures within the interior thereof. Base **20** also supports a human head-like arrangement, **22**, at its top containing control circuitry and supporting cameras **17**.

This structure and these actuators for this shoulder motion simulation are provided in an interior joint arrangement, **23**, that is supported on base **20** by two support structure plates, **24** and **25**, affixed thereto. These plates are seen in a plan view showing a portion of the FIG. **2** structure in FIG. **3**. Structure **25** supports a pair of rotary bases, **26** and **27**, each rotatably supporting a spindle of one of a pair of corresponding forks, **28** and **29**. The spindles of each of forks **28** and **29** can rotate within its corresponding one of rotary bases **26** and **27** along a vertical axis in FIGS. **1** and **2**, i.e. along a axis extending in the general direction of spine-like structure or base **20**. Rotary bases **26** and **27** support forks **28** and **29** while permitting them to rotate therein by having each corresponding fork spindle mounted in a pair of preloaded conical bearings, **30** and **31**, with each of the bearing members of a pair being located on an opposite end of its corresponding one of rotary bases **26** and **27**. The inner bearing races are affixed to the ends of the spindles of the forks, and the outer bearing races are affixed to the walls or rotary bases **26** and **27** at the opposite ends thereof.

The lower end of the spindle of fork **28** is fixedly attached to a bent, common shank, double clevis, **32**. Similarly, the lower end of fork **29** is fixedly attached to another bent, common shank double clevis, **33**. These double clevises are each driven by a corresponding linear actuator connected thereto and mounted on support structure **24**. A first of these linear actuators, **34**, is mounted on support structure **24** and rotatably connected in a clevis provided at one end of double clevis **32** by a pin. The other end of linear actuator **34** is connected through a pin to support structure **24** to be rotatably connected thereto. Similarly, a further linear actuator, **35**, is connected by a pin to a clevis structure at an end of double clevis structure **33** to be rotatably connected thereto, and the other end of linear actuator **35** is connected by a pin to support structure **24** to be rotatably connected thereto.

The upper end of fork **28**, opposite its end connected to double clevis **32**, has the two branches thereof forming a forked end rotatably connected by a pin to a tubular joint support, **36**. In a like manner, the upper end of fork **29**, opposite its end connected to double clevis **33**, has the two branches thereof forming a forked end rotatably connected through a pin to another tubular joint support, **37**. The opposite end of tubular joint support **36** has affixed to it a support bracket, **38**, supporting a ball-and-socket joint corresponding to a human shoulder joint as will be described below. This is also true of tubular joint support **37** which has affixed to it a further bracket, **39**, to support another ball-and-socket joint again corresponding to a human shoulder joint.

Thus, as can be seen in FIG. 3, if linear actuator **34** elongates, double clevis **32** will cause fork **28** to rotate in rotary base **26** thereby forcing tubular joint support **36** and the ball-and-socket connected thereto to rotate counterclockwise, and with rotation of the ball-and-socket joint held by bracket **38** occurring in the opposite direction for a shortening of linear actuator **34**. Similarly, any elongation of linear actuator **35** will cause double clevis **33** to rotate counterclockwise to thereby force fork **29** to rotate in rotary base **27** and thus force tubular joint support **37** and bracket **39** to rotate counterclockwise along with the ball-and-socket joint connected thereto. A shortening of linear actuator **35** will produce a rotation of that latter ball-and-socket joint in the opposite direction. Thus, slave robot **10** can emulate a human throwing his or her shoulders backward or forward by operation of linear actuators **34** and **35** to operate joint arrangement **23**.

Any such rotation of double clevis **32** results in moving a further linear actuator, **40**, as part of the same rotation because of the rotatable connection of the other clevis in double clevis **32** to linear actuator **40**. A similar result is achieved by linear actuator **35** rotating double clevis **33** to carry along in that rotation another linear actuator, **41**, rotatably connected to the remaining clevis in double clevis **33**. Linear actuator **40** has its opposite end rotatably connected to tubular joint support **36** at approximately a third of the length of that support away from its connection to fork **28**. Linear actuator **41** is similarly connected to tubular joint support **37** at approximately a third of its length away from its connection to fork **29**. Thus, operating linear actuators **40** or **41** to extend them up and down results in a motion of the corresponding ball-and-socket joint resembling shrugging motions in human shoulders.

The arrangement used to provide the back and forth motion of the shoulder-like ball-and-socket joints affixed to brackets **38** and **39** is, as described, accomplished by the use of linear actuators as shown in FIGS. **1**, **2** and **3**. Such a structure results in a very "stiff" arrangement in that forces applied to tubular joints supports **36** and **37** from external sources have relatively little effect in forcing those supports to move back and forth because of the strong resistance of linear actuators **34** and **35** to changing length due to external forces. However, other and simpler arrangements can be used for shoulder motion simulation joint **23** which may not be as resistant to externally applied forces but which are either cheaper or more convenient. Thus, linear actuators **34** and **35**, double clevises **32** and **33**, and rotary bases **26** and **27** can be dispensed with and replaced by a pair of side-by-side rotary electrical motors supported by a mount to base **20**. The output shafts of these motors have forked ends connected to tubular joint supports **36** and **37** as before, and also have thereon support brackets thereon extending therefrom down the sides of the motors and then underneath linear actuators **40** and **41** to thereby support them and rotate them. Such an arrangement would again allow rotating the shoulder-like ball-and-socket joints affixed to brackets **38** and **39** to similarly simulate the motion of human shoulders thrown back and forth. Linear actuators **40** and **41** would again be able to move joint supports **36** and **37** up and down with the ball-and-socket joints thereon to simulate the shrugging motion of human shoulders.

A further alternative for shoulder motion simulation joint **23** is to mount a pair support bases on base **20** in place of rotary bases **26** and **27** again dispensing with double clevis **32** and **33** and linear actuators **34** and **35** along with support structure **24**, and this time also dispensing with linear actuators **40** and **41**. Using these substituted bases, one for

each shoulder-like ball-and-socket joint, the joint supports **36** and **37** can each be directed outward in a sideways direction at an angle to the other and base **20**, and connected to its corresponding base by an orthogonal pivot structure such as a universal joint. Two outward extending arms on each base, extending in orthogonal directions therefrom, support rotatably connected linear actuators thereon, and the other ends of these actuators are rotatably connected to the facing side of a corresponding one of joint supports **36** and **37** at approximately the midpoint thereof. Tubular joint supports **36** and **37** are again connected by brackets at the ends thereof to the corresponding ball-and-socket joints. Suitably positioning the actuators with respect to base **20** allows one actuator to move the corresponding shoulder-like ball-and-socket joint back and forth, while the orthogonally positioned actuator is allowed to move that ball-and-socket joint up and down.

The ball-and-socket joints simulating shoulder joints of a human that are provided in control exoskeleton **12** worn by operator **11** are joined, although not shown in FIG. **1**, by the above described alternative version of joint **23** based on using a pair of electric motors with rotating output shafts to rotate the tubular joint supports front and back in aid of operator **11**. This use of such motors in control exoskeleton **12** in a joint having the purpose of joint **23** in slave robot **10** in place of the linear actuator implementation of joint **23** in slave robot **10** shown in FIGS. **2** and **3** is made to reduce the bulkiness of that structure for the comfort of operator **11** during use. The reduced resistance to externally applied forces in such a joint in control exoskeleton **12** is not a concern of the magnitude that it is for the joint **23** arrangement shown in FIGS. **1**, **2** and **3** for slave robot **10**, and not of the magnitude of the concern there would be for operator **11** if forced to wear an unduly bulky exoskeleton.

As indicated above, a pair of ball-and-socket joints, **42** and **43**, are provided at the end of tubular joint supports **36** and **37**, respectively, to permit simulating human shoulder joints which are known to be ball-and-socket joints capable of allowing the human arm to rotate therein to thereby make that arm capable of extending in a plurality of directions as can be seen in FIGS. **2** and **3**. Ball-and-socket joint **42** is supported by being affixed to bracket **38** which itself is affixed to the end of tubular joint support **36**. In a like matter, ball-and-socket joint **43** is supported by bracket **39** affixed thereto and to the end of tubular joint support **37**. Specifically, bracket **38** is affixed by screws to a socket, **44**, in joint **42**. Bracket **39** is also affixed by screws to a socket, **45**, in joint **43**. This can be more clearly seen in FIG. **4** for joint **42** which is a cross section view of that joint.

Within socket **44**, is a substantially hollow ball, **46**. Similarly, within socket **45** of joint **43** is a substantially hollow ball, **47**. Hollow balls **46** and **47** can rotate about their centers within sockets **44** and **45**, respectfully, to a considerable but limited extent by sliding along the interiors surfaces thereof. The limits to such rotation is provided by various protrusions from the balls (to be described below) encountering the terminating edges of sockets **44** and **45**. As one such protrusion, hollow ball **46** has affixed thereto a tubular ball extension, **48**. This is accomplished in a manner such that a open passageway through this joint exists extending through tubular joint structure **36**, through openings in bracket **38** and socket **44**, through hollow ball **46**, and then out therefrom through tubular ball extension structure **48**. This passageway permits electrical wiring to be brought from out of base **20** into the closest end of tubular joint support **36** and out the other end through bracket **38** and ball-and-socket joint **42** into tubular ball extension structure

48. Such wiring is used for controlling further actuators outward therefrom into the remaining structure connected thereto for simulating the human arm, and for collecting sensor information signals generated in such remaining structure.

A similar ball extension structure, 49, extends from hollow ball 47 forming a protrusion from that ball. A similar open passageway for wiring is thus provided is provided for joint 43 extending from the interior of tubular joint support 37, through bracket 39 and socket 45 into hollow ball 47, and then out through tubular ball extension 49. Again, such wiring is used for controlling further actuators outward therefrom into the remaining structure connected thereto for simulating the human arm, and for collecting sensor information signals generated in such remaining structure

Motions of ball extensions 48 and 49 are controlled for each by a corresponding pair of actuators mounted on an actuator support bracket. These support brackets are provided at an acute angle with respect to corresponding ones of joints support 36 and 37 such that the orientation of the long direction in these brackets lies more or less along a corresponding axis between it's associated ball-and-socket joint and spine-like structure, or base, 20. This angular arrangement has the effect of keeping the brackets and the pair of actuators supported thereby relatively close into the remaining torso-like structure of slave robot 10 to more easily enable providing additional structure over shroud 21 to protect the existing structure of slave robot 10 or to better simulate a human torso or both.

Ball-and-socket joint 42 has such an actuator support bracket 50, affixed to bracket 38 shown to extend back therefrom in FIG. 3 at an angle of approximately 25° with respect to tubular joint support 36 in that figure. Similarly, an actuator bracket, 51, is shown in FIG. 3 for ball-and-socket joint 43 extending back from bracket 39 to which it is affixed at a angle of approximately 25° with respect to tubular joint support 37. The selection of the value for this angle is based on a tradeoff between keeping the angle small to thereby improve compactness of the structure for slave robot 10, on the one hand, but having the angle large on the other hand so that the actuators supported thereby, generally aligned the major length of the support bracket therefor, retain the capability to force ball extensions 48 and 49 to rotate forward and back perpendicular to the corresponding tubular joint support for that ball-and-socket joint, i.e. to rotate about an axis substantially parallel to the direction of extension of those joint supports. Even more demanding in some situations, such rotations may be required to be directed to some degree inward toward the side of slave robot 10 at which the other ball-and-socket joint is located. The angular range of permitted choices for values of the angular relationships between the actuator support bracket and the tubular joint support in the plane of FIG. 3 is 15° to 75° depending on the strength of the structure, the force which can be generated by the actuator for the ball-and-socket joint responsible for moving tubular extension 48 or 49, and the expected load.

Actuator support bracket 51 is shown in greater detail in FIG. 5 where it can be seen that bracket 39 has both tubular joint support 37 and ball-and-socket joint actuator support bracket 51 affixed thereto. The portion of ball-and-socket joint actuator support bracket 51 affixed to bracket 39 is a long flat bar, 52, which has a clevis support plate, 53, affixed to the other end thereof. Clevis support plate 53 has a pair of branches, 54, forming a basis for a fixed position clevis affixed thereto. In addition, a further clevis support, 53', affixed to bar 52 approximately a quarter of the distance

therealong from clevis support plate 53 and approximately two thirds of its length, has rotatably connected to the opposite end thereof a more or less "U" shaped pair of branches and base, 55, forming the basis of a rotatably connected clevis.

Ball-and-socket joint actuator support bracket 50 in FIGS. 2 and 3 has a pair of linear actuators, 56 and 57, rotatably connected in the clevises of that bracket. Linear actuator 56 is rotatably connected at a end thereof to the fixed position clevis of bracket 50, and linear actuator 57 is rotatably connected at a end thereof to the rotatably connected clevis of bracket 50. The length of support plate 53' and the connection point of linear actuator 57 to ball extension 48 (to be described below) results in linear actuator 57 having an axis that in elevation makes an acute angle with the axis of linear actuator 56 to allow actuator 57 to apply more of the force generated thereby to ball extension 48 in forcing it to extend forward and retract backward. That angle seen in elevation should range from 15° to 75° to assure adequate force. Similarly, ball-and-socket joint actuator support bracket 51 has a further pair of linear actuators, 58 and 59, rotatably connected to the clevises therein in a similar arrangement. Linear actuator 58 has one end thereof rotatably connected to fixed clevis 54 of bracket 51, and linear actuator 59 has one end thereof rotatably connected to rotatably connected clevis 55 of bracket 51.

Linear actuator 56 is rotatably connected at an end thereof, opposite the one connected to bracket 50, to a bent pin, 60. Pin 60 is bent to approximately a right angle and has the portion thereof past the bend away from its connection to linear actuator 56 extending through slots in socket 44 on opposite sides thereof and through the outer wall of ball 46 twice on opposite sides thereof. As can be seen in FIG. 4, the portion of bent pin 60 extending through ball 46 and through corresponding slots in socket 44 extends through the center of ball 46. The presence of the portion of bent pin 60 past the bend extending through ball 46, but captured in the slots in socket 44, prevents ball 46 from rotations along an axis through the center thereof other than parallel to the axis of that portion of pin 60. Yet, ball 46 can rotate about the axis of the portion of pin 60 therethrough thus allowing tubular ball extension 48 to rotate more or less in and out of the plane of the drawing in FIG. 4 but preventing twisting of that extension about other axes in the plane of that figure. Furthermore, extensions and retractions of linear actuator 56 rotate ball 46 about an axis perpendicular to the plane of FIG. 4 to thus guide the angular orientation of tubular ball extension 48 with respect to tubular joint support 36. This orientation will determine the direction towards which tubular ball support 48 is pointing with respect to tubular joint support 36 when extension 48 is forced up from or into the plane of FIG. 4 by linear actuator 57 to be described below.

A similar bent pin, 61, is rotatably connected to the end of linear actuator 58 opposite that end thereof which is connected to bracket 51, and the portion of bent pin 61 past the bend extends through slots in socket 45 and through the wall of ball 47 twice in a manner similar to bent pin 60. Note in FIG. 4 that bent pin 60 is retained in ball 46 by a pair of retaining rings, 62 and 63, positioned against the walls of ball 46. A similar arrangement is used to retain bent pin 61 in ball 47.

The end of linear actuator 57 not connected to the rotatable clevis in bracket 50 is connected to tubular ball extension 48 through a slip ring arrangement, 64. Slip ring arrangement 64 has an inner bearing race affixed to tubular ball extension 48. An outer bearing race is rotatably connected by pins to a pair of arms extending from linear

actuator **57**. Needle bearings are used between the inner and outer races of slip ring **64**. A similar slip ring, **65**, is provided about tubular ball extension **49** for the rotatable connection of linear actuator **59** thereto. The extensions and contractions of linear actuators **57** or **59** force tubular ball extensions **48** or **49** toward or away from the rotatably connected clevises of the corresponding ones of actuator brackets **50** and **51** to thus simulate the motion of a human arm being extended or retracted. The orientation of that extension, is described above, is controlled by linear actuators **56** and **58** in orienting the axis of bent pin **60** and **61**, respectfully, to orient the location of corresponding balls **46** and **47**.

Below tubular ball extensions **48** and **49** are the structures used to simulate motion of a human forearm about the elbow. The human elbows are simulated by single degree-of-freedom joints in slave robot **10**, such a single degree-of-freedom joint, **70**, being supported by tubular ball extension **48**. Tubular ball extension **49** supports a similar single degree-of-freedom joint, **71**. Tubular ball extension **48** supports joint **70** by supporting a tubular joint base, **72**, rotatably attached thereto through a pair of bearings having inner races attached to tubular joint base **72** and outer races attached to tubular ball extension **48** which cannot be seen in the drawings. The bottom of tubular ball extension **48** has therearound a set of gear teeth, **73**. A motor, **74**, affixed to tubular joint base **72** forces that base and motor **74** to rotate within tubular ball extension **48** in the bearings just described through a gear on the output shaft thereof engaged with gear **73**. Thus, single degree-of-freedom joint **70** and the apparatus there beyond can be caused to rotate with respect to tubular ball extension **48**.

A similar structure is provided in connection with tubular ball extension **49** and single degree-of-freedom joint **71**. Tubular ball extension **49** supports a tubular joint base, **75**, through a pair of bearings between them not seen in the figures in the same arrangement as used in connection with tubular ball extension **48** and tubular joint base **72**. The end of tubular ball extension **49** has a gear thereabout, **76**, and tubular joint base **75** can be rotated within tubular ball extension **49** and the bearings just mentioned by a motor, **77**, through a gear on the output shaft thereof engaged with gear **76**.

FIG. **6** shows more detail in a selected one of joints **70** and **71**, here joint **70**. As can be seen, a linear actuator, **80**, is used to force the side of joint **70** opposite tubular joint base **72** into motions relative to that base. Linear actuator **80** is rotatably connected at one end thereof to a bracket, **81**, which is mounted on tubular joint base **72** as can be more easily seen in the cross section view of FIG. **7**. The opposite end of linear actuator **80** is connected to a flexible mechanical drive tape, **82**, guided in a pair of tape guides, **82'**, by a tape connector, **83**, mounted on that end of actuator **80** which can be better seen in the cross section view of FIG. **8**. A linear variable differential transformer, **84**, is held by a bracket, **85**, to tubular joint base **72**, and has its movable core, **86**, connected by a connector, **87**, to the same end of actuator **80** as is tape **82**.

A tubular joint extension, **88**, shown in FIG. **6** is subject to being rotated both clockwise and counterclockwise in the view of that figure about a end portion of tubular joint base **72** opposite that end thereof engaged with tubular ball extension **48** in accord with the single degree-of-freedom permitted joint **70**. The bearing arrangement to allow such rotation of joint extension **88** is best seen in FIG. **9** where it can be seen that tubular joint base **72** expands at the rotational axis location of joint **70** to form on one side thereof a cup-like portion **89** (in which there is provided a

removable plate to permit external access) supporting a portion of and enclosing, except for a side facing away from the rest of the cup, a circular bearing holder band, **90**, with an open interior space. A pair of thin section angular contact bearings, **91**, are fitted within the circular open interior space provided by bearing position band **90** on opposite sides of that band with the bearing outer races connected to the inner surface of this band.

Joint extension **88** also expands in the portion thereof at the rotational axis of joint **70** by forming a rectangular space a rectangular offset tub, **92**, which has extending from the wall thereof farthest from the remainder of extension **88** within the rectangular space a truncated cylindrical shell, **93**. Truncated cylindrical shell **93** has an outer diameter to permit it to fit within the circular open interior space of bearing holder band **90** of tubular joint base **72**, and within bearings **91**, so that the inner race of these bearings is connected to the outer surface of truncated cylindrical shell **93** so as to enable this shell to rotate within bearing holder band **90**.

Joint extension **88** is driven in and out of the plane of FIG. **9** by mechanical drive tape **82** being fastened about the outer surface of truncated cylindrical shell **93** of that extension between the pair of bearings **91** to thereby be subject to being rotationally moved by movements of linear actuator **80** forcing that tape to correspondingly move. Mechanical drive tape **82** is fastened to the outer surface of truncated cylindrical shell **93** by pin, **94**, seen in the cross section view of FIG. **10**. There, mechanical drive tape **82** can be seen to pass through a slot in cup-like portion **89** of tubular joint base **72** to be wrapped around and pinned to the outer surface of truncated cylinder **93**.

Thus, movement of linear actuator **80** in FIG. **10**, thereby forcing upward the end of tape **82** connected to it, will lead to clockwise motion of joint extension **88**, and downward motion of linear actuator **80** will lead to counterclockwise motion of joint extension **88**. This is possible because mechanical drive tape **82** is a rugged but flexible polymer material designed for such service and sold under the trademark DYMETROL®. An advantageous result of using such a mechanical tape drive to transmit movement force to joint extension **88** from linear actuator **80** is the providing of an open passageway through the interior of the tubular joint base **72**, through it's cup-like region **89**, and then through truncated cylinder **93** and rectangular offset portion **92** of joint extension **88**. This again is allows wiring to be passed therethrough and on to further locations in the apparatus of slave robot **10** beyond joint **70**.

Single degree-of-freedom elbow-like joint **71** also has a tubular joint extension, **95**, shown in FIG. **2** that is subject to be rotated upward and downward in that figure with respect to extension **49**. Extending from each of joint extensions **88** and **95** are the remainder of the structures of slave robot **10** which are used to simulate the human forearm, the human wrist and the human hand. The human forearm is simulated by joint tubular base, **96**, supported by tubular joint extension **88** with joint base **96** being rotatably attached to joint extension **88** through a pair of bearings having inner races attached to tubular joint base **96** and outer races attached to tubular joint extension **88** which cannot be seen in the drawings. The bottom of joint extension **88** has therearound a set of gear teeth, **97**. A motor, **98**, affixed to tubular joint extension **88** forces tubular joint base **96** to rotate within extension **88** in the bearings just described through a gear on the output shaft of that motor engaged with gear **97**.

Similarly, joint extension **95** supports a joint tubular base, **99**, simulating a human forearm rotatably attached thereto

through a pair of bearings having inner races attached to tubular base 99 and outer races attached to extension 95 which cannot be seen in the drawings. The bottom of extension 95 has there around a set gear teeth, 100. A motor, 101, affixed to tubular joint extension 95 forces tubular joint base 99 to rotate within extension 95 in the bearings just described through a gear on the output shaft of the motor engaged with gear 100.

Further in FIG. 2, joint tubular base 96 supports a wrist-like joint, 102, and joint tubular base 99 supports a wrist-like joint, 103. Wrist-like joint 102 supports a hand-like structure, 104, and wrist-like joint 103 supports a hand-like structure, 105.

Hand-like structure 105 is shown in greater detail in a front pictorial view thereof in FIG. 11, and in a rear pictorial view thereof in FIG. 12. As can be seen there, joint tubular base 96 in turn supports a pedestal and mounting block arrangement, 110, on which wrist-like joint 102 is mounted. Also supported on tubular base joint 96 is a drive motor, 111, clamped thereon by split clamp having a first clamp portion, 112, affixed to drive motor 111 and a separated second clamp portion, 113, which goes on the opposite side of joint tubular base 96 and a part of mounting block arrangement 110. When clamp portions 112 and 113 are brought together around portions of base 96 and arrangement 110 and clamped together by machine bolts (not shown) extending from one clamp portion to the other, motor 111 is firmly affixed to base 96 and arrangement 110.

Also affixed to joint tubular base 96 is a transducer bracket, 114, which has a circular opening therein to allow it to be slid over joint tubular base 96 against which it is tightened by a set screw not shown. Transducer bracket 114 has a spaced apart pair of arms extending therefrom with a valley in each covered by a clamping bracket, 115, to accept and rotatably hold in these valleys a solid pivot pin, 116, (seen only in FIG. 13 introduced below) extending from one side of a transducer holder, 117, and a center tapped pivot pin, 118, extending from the other side thereof. Pin 118 has a set screw therein which affixes holder 117 to the outer cylindrical shell body, 119, of a linear variable differential transformer, 120, positioned in a hole provided through holder 117 at right angles to the axis of the pins therein. An internal shaft, 121, of transducer 120 is affixed at the other end thereof in a yolk, 122. Yolk 122 is rotatably attached to a drive housing framing block, 123, by a pivot pin, 124, extending through the two sides of yolk 122 and an extension boss, 125, of framing block 123 which boss is positioned between those sides. Linear variable differential transformer 120 serves as a displacement measure transducer to indicate effectively the angular displacement of a drive housing that includes framing block 123 due to actions of motor 111.

This drive housing is shown in an exploded view of wrist-like joint 102 in FIG. 13, and is there shown formed of a further drive housing framing block, 126, positioned in joint 102 opposite framing block 123, and two drive housing sectorial frames, 127 and 128, spaced apart but joined together by these two framing blocks. Drive housing framing blocks 123 and 126 are connected to drive housing sectorial frames 127 and 128 by machine screw and pin sets, 129. In each of drive housing sectorial frames 127 and 128 are provided bearing races, 130, in which ball bearings, 131, are positioned. Ball bearings 131 are held in bearing races 130 by drive housing sectorial mounts, 132 and 133. Mounts 132 and 133 each have bearing races, 134, in which ball bearings 131 are positioned as well as in races 130 of the corresponding one of drive housing sectorial frames 127 and 128 where they are held with these frames clamped against those mounts. Pins, 135, are provided at the opposite ends of the bearing races 134 to keep ball bearings 131 contained in races 130 and 134. Framing mounts 132 and 133 are affixed to mounting block 110 by a pair of machine screw and pin sets not shown.

In addition, drive housing sectorial frames 127 and 128 support a motor mount structure therebetween to be described below held thereto by a pair of machine screw and pin sets, 136. Drive housing sectorial frame 127 further has a sectorial bevel gear, 137 affixed thereto by machine screw and pin sets 129. Sectorial bevel gear 137 and drive housing sectorial frame 127 are driven together, and so also the drive housing, along the sectorial track of that bevel gear by a beveled pinon gear, 138, mounted on the output shaft of drive motor 111. Thus, the frame of the drive housing, formed of drive housing framing blocks 123 and 126 together with drive housing sectorial frames 127 and 128, is driven about an axis perpendicular to the axis joining two accommodational openings, 139, for ball bearing assemblies in drive housing framing blocks 123 and 126.

Each of ball bearing assembly accommodational openings 139 (only one of which is seen in FIG. 13) accommodate a corresponding preloaded ball bearing assembly, 140 and 141. The inner races of ball bearing assemblies 140 and 141 are press fitted on corresponding shafts, 142 and 143, each of which have a raised ring machined thereabout located at approximately the center thereof serving as spacers.

The opposite ends of shafts 142 and 143 are pressed fit into openings in a further output yolk, 144, serving as the joint 102 output structure supporting hand-like structure 104. Further affixed to one side of output yolk 144 is a sector gear, 145, through which shaft 143 passes into yolk 144. Sector gear 145 is affixed to the side of yolk 144 by machine screws not shown.

A drive housing motor support, 146, is, as previously mentioned, connected to drive housing sectorial frames 127 and 128 by machines screw and pin sets 136. Motor support 146 supports a further drive motor, 147, on an axis orthogonal to that about which the output shaft of drive motor 111 rotates. Drive motor 147 is mounted on motor support 146 by machine screws not shown extending through that mount into a flange on the face of drive motor 147. The output shaft of drive motor 147 extends through motor support 146 into a pinon gear, 148, engaged with sector gear 145 and which also drives an idler gear, 149, which is rotatably mounted on motor support 146 by a shoulder screw, 150. Idler gear 149, in turn, drives a further gear, 151, mounted on a threaded shaft, 152, which also extends through motor support 146. Rotation of gear 148 by motor 147 forces sector gear 145 and output yoke 144 to also rotate about the axis through shafts 142 and 143 so that hand-like structure 104 mounted on yoke 144 can be rotated to a desired angle by the combined motions provided by operating both motors 111 and 147.

Threaded shaft 152 extends into a threaded nut (not seen) in a translation carriage, 153. Thus, rotation of gear 148 by motor 147, and so rotation of gears 149 and 151, also causes threaded shaft 152 to rotate which in turn forces the nut in carriage 153 to move linearly along threaded shaft 152 thus translating rotation motion of gear 151 to linear motion of carriage 153. Carriage 153 is affixed to an output shaft, 154, belonging to a linear variable differential transformer, 155, used to measure the linear displacement of carriage 153 and thus the number of revolutions of drive motor 147 from a reference point. Hence, the angular displacement of output

yoke **144** can be effectively measured. Linear variable differential transformer **155** is supported at its opposite end in a clamp, **156**, placed around it and the base of drive motor **147**. Clamp **156** is tightened by a machine screw, **157**, and linear variable differential transformer **155** can be tighten in clamp **156** by use of a setscrew, **158**.

Returning to FIGS. **11** and **12**, hand-like structure **104** is supported on output yoke **144** by a slave support frame, **160**, at a slave support base, **161**, therein that is fastened to yoke **144** with machine screws, **162**. Support frame **160** is better seen in FIG. **14** where a first extension, **163**, extends from support base **161** to the right in that figure to thereafter curve around behind that base. A small subextension, **164**, extends out from both base **161** and first extension **163** in a forward direction in that figure with a recess therein, not seen, that has a surface following a portion of a spherical surface. A frame cap plate, **165**, with a recess therein having a surface also following a portion of a spherical surface, again not seen, is fastened to base **161**, first extension **163**, and subextension **164** to trap therebetween in the recesses a ball support, **166**, having at least a portion of its surface following the surface of a portion of a sphere. Extending from ball support **166** is a tube support, **167**, that passes through a second, opposite side access opening to the recess in frame cap plate **165** to be further described below. Tube support **167** and ball support **166** both have a common opening extending therethrough which meets another opening between frame cap plate **165** and both first extension **163** and subextension **164** to permit actuator and sensor wiring to extend from frame support **160** into that which is supported on tube support **167** to be described below.

Slave support frame **160** has a second extension, **168**, rotatably connected to support base **161** by a shouldered sleeve, **169**, fastened to base **161** by a machine screw, **170**. Extension **168** extends to the left in FIG. **14** from its rotary connection to base **161** and then curves around behind that base to be rotatably connected to a linear actuator, **171**, by a pivot pin, **172**, passing through the opposite sides of the outer moveable body of actuator **171** and through a hole through the end of second extension **168** positioned between these two sides.

The opposite, or base, end of linear actuator **171** is rotatably connected in a yoke, **173**, formed at the end of first extension **163** by a pivot pin, **174**, passing through the two sides of yoke **173** and the base end of actuator **171**. Thus, the outer moveable body of actuator **171**, in being activated to travel back and forth with respect to the end thereof held in yoke **173** forces second extension **168** to rotate clockwise and counterclockwise with respect to support base **161**. The degree of such rotation is measured by a linear differential variable transformer, **175**, fastened to both the base end and the outer body of linear actuator **171** to measure the distance one has traveled with respect to the other. A machined spring is also formed at the base of linear actuator **171**, and a linear variable differential transformer not seen is provided thereacross to measure the elongation or contraction of that spring to thereby measure the force on actuator **171**.

Rotatably mounted to first extension **163** are a pair of clevises, **176** and **177**, by sleeves and machine screws not shown. Similarly, rotatably mounted to second extension **168** are a pair of clevises, **178** and **179**, again by sleeves and machine screws not shown. Each of these clevises in each of these pairs thereof has the base end of a corresponding linear actuator rotatably mounted therein, as can be seen in FIG. **11**, by a corresponding pivot pin not seen. Thus, clevis **176** is rotatably connected to a corresponding linear actuator, **180**. Similarly, clevis **177** is rotatably connected to a corresponding linear actuator, **181**. In the remaining pair of clevises connected to second extension **168**, clevis **178** is rotatably connected to a corresponding linear actuator, **182**, and clevis **179** is rotatably connected to a corresponding linear actuator, **183**.

Two further support items are mounted in slave support frame **160** as assembled for use, one in an opening, **184**, in frame cap plate **165** over first extension **163** and the other in an opening, **185**, in second extension **168** as seen in FIG. **14**. These support items are support ball pedestal tubes, there being a support pedestal, **186**, fixedly mounted in opening **184** and another support pedestal, **187**, fixedly mounted in opening **185** as seen in FIG. **11**. Pedestal **186** supports a fixedly attached pedestal ball, **188**, having at least a portion of its surface following the surface of a portion of a sphere. Similarly, pedestal **187** supports a fixedly attached pedestal ball, **189**, also having at least a portion of its surface following the surface of a portion of a sphere. The pedestal and the ball in each of these pedestal and support ball combinations both have a common opening extending therethrough to permit actuator and sensor wiring to extend therethrough, as can be seen for pedestal ball **189** in FIG. **11** where the structure actually surrounding it has been partially broken away in that view to expose a portion of that pedestal ball.

Pedestal **186** and pedestal ball **188** support an effector base, **190**, with a ball capture lip structure, **191**, surrounding the bottom thereof to capture pedestal ball **188** therein as seen in FIG. **11**. The opening in effector base **190** and ball capture lip structure **191** has an interior surface of which at least a portion follows a spherical surface to thereby allow effector base **190** and ball capture lip structure **191** to rotate around pedestal ball **188** in any direction, i.e. to be capable of rotating in orthogonal directions therearound. Ball capture lip structure **191** has two outward extensions on the rear side thereof to form a yoke, **192**, seen in part in both FIGS. **11** and **12**. Effector base **190**, ball capture lip structure **191**, and yoke **192** are formed from two half structures split along the length thereof, more or less vertically in FIGS. **11** and **12**, which are brought together to capture pedestal ball **188** therebetween and are thereafter held together by a pair of machine screws, **193**.

Similarly, pedestal **187** and pedestal ball **189** support another effector base, **194**, with a ball capture lip structure, **195**, surrounding the bottom thereof to capture pedestal ball **189** therein as again seen in FIG. **11**. The opening in effector base **194** and ball capture lip structure **195** has an interior surface of which at least a portion follows a spherical surface to thereby allow effector base **194** and ball capture lip structure **195** to rotate around pedestal ball **189** in any direction, i.e. to be capable of rotating in orthogonal directions therearound. Ball capture lip structure **195** has two outward extensions on the rear side thereof to form a another yoke, **196**, seen in part in both FIGS. **11** and **12**. Here too, effector base **194**, ball capture lip structure **195**, and yoke **196** are formed from two half structures split along the length thereof, more or less vertically in FIGS. **11** and **12**, which are brought together to capture pedestal ball **189** therebetween and are thereafter held together by a pair of machine screws, **197**.

Effector base **190** is forced to rotate about pedestal ball **188** by linear actuators **180** and **181**, the base ends of which are rotatably connected to first extension **163** on either side of pedestal **186** mounted in frame cap plate **165** at opening **184** through being rotatably connected by pivot pins to clevises **176** and **177**, respectively, as described above. The opposite ends of actuators **180** and **181** have at the extremes

thereof a ball on a base, or short pedestal, captured in a socket in the nearest arm of yoke **192** on either side of the opening in base effector **190** and ball capture lip structure **191** in which pedestal ball **188** is captured. Thus, actuator **181** has a ball, **198**, on its outer body moveable end which is captured in an opening formed in the nearest arm of yoke **192** and a capture plate, **199**, fastened thereto as seen in FIG. **11**. This opening again has an interior surface at least a portion of which follows a portion of a spherical surface. The ball on the outer body moveable end of actuator **180** cannot be seen in FIG. **11**, nor can it be seen in FIG. **12**. However, a capture plate, **200**, for capturing this unseen ball at this end of actuator **180** can be seen in the view in FIG. **12**.

Linear actuators **180** and **181** are capable of forcing effector base **190** to any angle with respect to vertical within a limited angular range about the vertical in FIGS. **11** and **12** substantially followed by the length axis of effector base **190** in the straight-up position thereof in those figures. Extending or retracting the moveable ends of actuators **180** and **181** in unison forces effector base **190** forward and backward in the views of these figures with the combined forces supplied by each actuator, while differentials in the motions between the moveable ends of these actuators result in side-to-side motions of effector base **190**. As a result, combinations of such motions allow choosing any desired angle for effector base **190** within the limited range. The angular range possible for effector base **190** is clearly limited mechanically by interference between ball capture lip structure **191** and pedestal **186**, by the maximum excursion of the moveable ends of actuators **180** and **181** from the base ends thereof, and by the location of effector base **194** and the location of an opposing effector base not yet described. Practically, however, the angular range limits for effector base **190** will be established by operating controls on actuators **180** and **181** to limit the excursions of the moveable end thereof with respect to the corresponding end.

Similarly, effector base **194** is forced to rotate about pedestal ball **189** by linear actuators **182** and **183**, the base ends of which are rotatably connected to second extension **168** on either side of pedestal **187** mounted in opening **185** in that extension through being rotatably connected by pivot pins to clevises **178** and **179**, respectively, as described above. The opposite ends of actuators **182** and **183** also have at the extremes thereof a ball on a base, or short pedestal, captured in a socket in the nearest arm of yoke **196** on either side of the opening in base effector **194** and ball capture lip structure **195** in which pedestal ball **189** is captured. Thus, actuator **183** has a ball, **201**, on its outer body moveable end which is captured in an opening formed in the nearest arm of yoke **192** and a capture plate, **202**, fastened thereto as seen in FIG. **11**. This opening again has an interior surface at least a portion of which follows a portion of a spherical surface. The ball on the outer body moveable end of actuator **182** cannot be seen in FIG. **11**, nor can it be seen in FIG. **12**. However, a capture plate, **203**, for capturing this unseen ball at this end of actuator **182** can be seen in the view in FIG. **12**.

In the same manner, linear actuators **182** and **183** are capable of forcing effector base **194** to any angle with respect to vertical within a limited angular range about the vertical in FIGS. **11** and **12** substantially followed by the length axis of effector base **194** in the straight up position thereof in those figures. Here again, extending or retracting the moveable ends of actuators **182** and **183** in unison forces effector base **194** forward and backward with the combined forces of each actuator in the views of these figures, while differentials in the motions between the moveable ends of these actuators result in side-to-side motions of effector base **194**. Thus, combinations of such motions allow choosing any desired angle for effector base **194** within the limited range. The angular range possible for effector base **194** is limited in the same way as that for effector base **190**.

The angular position achieved by either of effector bases **190** or **194** is measured in the manner that the angular position of second extension **168** in support frame **160** is determined, that is, by use of a linear variable differential transformer like transformer **175** measuring the extension of the moveable end of the corresponding linear actuators with respect to the base end thereof. Thus, in FIG. **12**, linear actuator **180** has a linear variable differential transformer, **204**, connected between its base and moveable ends; linear actuator **181** has a linear variable differential transformer, **205**, connected between its base and moveable ends; linear actuator **182** has a linear variable differential transformer, **206**, connected between its base and moveable ends; and linear actuator **183** has a linear variable differential transformer, **207**, connected between its base and moveable ends.

The force appearing along the length axis of each of linear actuators **180, 181, 182** and **183** is also measured through the use of machined springs formed in a cylindrical block of material at the base ends of these actuators where this forming is accomplished by sawing slits into the cylindrical block. The remaining material forms a high spring constant spring with the deflection thereof being a measure of the applied force. That deflection is measured by a further linear variable differential transformer mounted across the ends of the machined springs in these actuators. Again in FIG. **12**, linear actuator **180** has a linear variable differential transformer, **208**, connected across the ends of its machined spring, **209**, formed at its base end; linear actuator **181** has a linear variable differential transformer, **210**, connected across the ends of its machined spring, **211**, formed at its base end; linear actuator **182** has a linear variable differential transformer, **212**, connected across the ends of its machined spring, **213**, formed at its base end; and linear actuator **183** has a linear variable differential transformer, **214**, connected across the ends of its machined spring, **215**, formed at its base end.

Effector base **190** has a first gripping extension, **216**, rotatably connected thereto at the end thereof opposite that in which pedestal ball **188** is captured as seen in FIGS. **11** and **12**. Extension **216** has a yoke like end with two extensions between which a portion of effector base **190** is held by a pivot pin, **217**, extending therethrough. A linear actuator, **218**, has a base end thereof rotatably connected by a pivot pin, **219**, between the extensions of yoke **192**. The moveable end of actuator **218** is rotatably connected between a pair of extensions forming a yoke, **220**, in first gripping extension **216** by a pair of pivot pins, **221**. Extensions and retractions of linear actuator **218** forces first gripping extension **216** to rotate forward and backward about pins **221** with respect to effector base **190**. A linear variable differential transformer, **222**, again measures the displacement between the base and moveable ends of actuator **218** to measure the degree of this rotation.

A second gripping extension, **223**, has a portion thereof rotatably connected to first gripping extension **216** between portions thereof forming a further yoke by a pin, **224**, at its end opposite the end having a yoke connected to effector base **216**. This gear is engaged with gears not seen in first gripping extension **216** forcing second gripping extension **223** to rotate with respect to first gripping extension **216** when the latter is rotated with respect to effector base **190**.

Similarly for effector base **194**, that base has a first gripping extension, **225**, rotatably connected thereto at the end thereof opposite that in which pedestal ball **189** is captured as seen in FIGS. **11** and **12**. Extension **225** has a yoke like end with two extensions between which a portion of effector base **194** is held by a pivot pin, **226**, extending therethrough. A linear actuator, **227**, has a base end thereof rotatably connected by a pivot pin, **228**, between the extensions of yoke **196**. The moveable end of actuator **227** is rotatably connected between a pair of extensions forming a yoke, **229**, in first gripping extension **225** by a pair of pivot pins, **229'**. Extensions and retractions of linear actuator **227** forces first gripping extension **225** to rotate forward and backward about pins **229'** with respect to effector base **194**. A linear variable differential transformer, **230**, again measures the displacement between the base and moveable ends of actuator **227** to measure the degree of this rotation.

A second gripping extension, **231**, has a portion thereof rotatably connected to first gripping extension **225** between portions thereof forming a further yoke by a pin, **232**, at its end opposite the end having a yoke connected to effector base **225**. Pin **232** also has a gear centrally mounted thereon. This gear is engaged with gears not seen in first gripping extension **225** forcing second gripping extension **231** to rotate with respect to first gripping extension **225** when the latter is rotated with respect to effector base **194**.

An opposed effector subbase, **233**, is mounted on a narrowed, upper portion of tube support **167** in FIG. **14** over a carrier bracket, **234**, clamped to a wider, lower portion of that support by a set screw not shown. A socket former, **235**, is attached to opposed effector subbase **233** by machine screws not shown. Thus, opposed effector subbase **233**, carrier bracket **234** and socket former **235** are all rotatable together on ball support **166** to the extent permitted by the access opening in frame cap plate **165** through which tube support **167** extends.

These components assembled appear in FIGS. **11** and **12** where carrier bracket **234** has the two extended sides thereof curving downward in those figures form a yoke in which the base end of a linear actuator, **236**, is rotatably held by a pivot pin, **237**, passing therethrough and through the sides forming the yoke. The moveable end of actuator **236** is also rotatably connected by a pivot pin, **237'**, in a yoke formed in an opposed gripping base, **238**. Opposed gripping base **238** is rotatably connected to both an opposed gripping extension, **238'**, and to opposed effector subbase **233**, this latter rotary connection made by a pivot pin, **239**.

The rotatable connection of opposed gripping base **238** to opposed gripping extension **238'** is made by a further pivot pin, **239'**. Pin **239'** also has a gear centrally mounted thereon. This gear is engaged with gears not seen in opposed gripping base **238** forcing opposed gripping extension **238'** to rotate with respect to opposed gripping base **238** when the latter is rotated with respect to opposed effector subbase **233**. Linear actuator **236** forces opposed gripping base **238** to rotate with respect to opposed effector subbase **233**, and the extent of this rotation is again measured by the displacement between the base and moving ends of this actuator. This displacement measurement is made by a linear variable differential transformer, **240**. Force on this actuator is measured by use of a machined spring, **241**, in the base end thereof with its displacement measured by a further linear variable differential transformer, **242**.

Circumferential motion of opposed effector subbase **233** on tube support **167** and ball support **166** with respect to first extension **163** and subextension **164** to simulate such motion

of the human thumb is provided by two further linear actuators, **243** and **244**, which extend and retract at approximately right angles to one another to provide such motion. Actuator **243** has a machined spring, **245**, in the base thereof and a short pedestal, **245'**, supporting a ball not seen on the moveable end thereof. Actuator **243** has this base end thereof rotatably connected by a pivot pin, **246**, in a clevis, **247**, which is rotatably connected in an opening, **248**, in a support extension, **249**, of frame support **160** seen in FIG. **14**. The moveable end of actuator **243** has the unseen ball at its extreme on short pedestal **245'** captured in the opening provided by opposed effector subbase **233** and socket former **235**. This opening has an interior surface of which at least part follows a portion of a spherical surface to allow the ball captured to rotate therein. A linear variable differential transformer, **250**, measures translation between the base and moveable ends of actuator **243**, and a further linear variable differential transformer, **251**, measures the elongation and compaction of machined spring **245**.

Linear actuator **244** has a machined spring, **252**, in the base thereof and has this base end rotatably connected by a pivot pin, **253**, in a clevis, **254**, which is rotatably connected in an opening, **255**, in first frame extension **163** of frame support **160** seen in FIG. **14**. The moveable end of actuator **244** is rotatably connected by a pivot pin, **256**, in a clevis, **257**, which is rotatably connected into opposed effector subbase **233**. A linear variable differential transformer, **258**, measures translation between the base and moveable ends of actuator **244**, and a further linear variable differential transformer, **259**, measures the elongation and compaction of machined spring **252**.

FIG. **15** shows a pictorial view of a linear actuator, **260**, similar to those used in slave robot **10** described above and in control exoskeleton **12**. A base, **261**, contains an electrical motor to rotate a shaft mounting an exterior helical screw thread arrangement, **262**, and a shaft encoder to provide electricals indicating these rotations. Shaft exterior screw thread arrangement **262** is engaged with an interior screw thread arrangement, **263**, at the inner surface of a moveable cylindrical body or end, **264**, of linear actuator **260**. Moveable end **264** is shown formed with a yoke, **265**, at the end thereof, but slave robot **10** also used such linear actuators having instead a ball on a pedestal at the extreme of the moveable end thereof.

A machined spring, **266**, formed by sawing slits into a cylindrical metal block provided in base **261**, provides a portion of a force measuring sensor through its elongating or compressing in proportion to the tensile or compression forces provided thereon, the resulting elongation or compression being measured by a linear variable differential transformer, **267**, connected on opposite sides of spring **266** as part of the sensor. The elongation of spring **266** permitted is limited by a retainer, **267'**, also connected on opposite sides of that spring, to thereby prevent inelastic extensions thereof under sufficiently large tensile forces.

The translation of moveable end **264** with respect to base end of spring **261** has been typically measured by a further linear variable differential transformer having one end connected to each as has been shown for the linear actuators described above, but a cheaper though less accurate alternative is shown in FIG. **15** in the form of an electrical switch, **268**, which is caused to switch between open and closed by a tab, **269**, extending from the near end of moveable body **264**, to set positional reference point for that body. Translation of body **264** from that point is then kept track of by the signals provided by the shaft encoder in base **261**. A further alternative not shown is the use of a sliding wiper

potentiometer connected to both base end **261** and moveable end **264** to measure translations therebetween.

Various force sensing pads, **270**, are provided on the gripping surfaces of hand-like structure **104** as seen in FIG. 11, including over a cover cushion, **271**, mountable on pedestals **186** and **187** for providing a smooth surface to grip objects against. The electrical wiring used to interconnect these pads with the transmitter in slave robot **10** in communication with system controller **15** is not shown. Pads **270** are typically formed by two sheets of closely spaced electrical conductors positioned to have the conductors in each sheet orthogonal to those in the other to in effect form a grid with each sheet of wiring separated form the other by a material which reduces its electrical conductivity with increasing force thereon. The locations in the grid with reduced electrical resistance between conductor cross over points can be determined to indicate the location and magnitude of the applied force which is conveyed to system controller **15**.

As indicated above, bodily motion based force magnitude signals (and some translation magnitude signals) derived from signals generated in control exoskeleton **12** during its operation are used by control arrangement **13** to cause similar motions by the above described similar actuators in slave robot **10** through control arrangement **13** transmitting such signals to slave robot **10**. Such signals generated in control exoskeleton **12** during its operation are generated by sensors located in the various portions of control exoskeleton **12** adjacent actuators used in those portions. Examples of portions of control exoskeleton **12** having such actuators along with appropriate sensors are provided by a pair of wrist-like joints, **280** and **281**, supporting a pair of corresponding hand-like structures, **282** and **283**. Control exoskeleton **12** receives signals from control arrangement **13** based on the signals control arrangement **13** received from the sensors in these portions and uses the information in those signals to operate the corresponding actuators in slave robot **10**, and also in control exoskeleton **12** to aid human operator **11** in moving the exoskeleton apparatus to the extent desired by that operator. That is, the signals received in control exoskeleton **12** from control arrangement **13** are used to move the corresponding actuators therein sufficiently to null out force magnitude signals measured by force sensors thereon due to forces imposed by bodily motions of human operator **11** which force signals (and some translation magnitude signals) were transmitted to control arrangement **13**.

Wrist-like joint **280** and hand-like structure **282** are shown in more detail in a front pictorial view thereof in FIG. **16** and in a corresponding rear pictorial view in FIG. **17**. Wrist-like joint **280** has essentially the construction of wrist-like joint **102** in FIGS. **11**, **12** and **13** except for the force actuators used. The force actuators in wrist-like joint **280** are provided by a pair of linear actuators, **283** and **284**, rather than by electrical motor **111** with pinion **138** and electrical motor **147** with pinion **148** driving corresponding sector gears **137** and **145** used in joint **102**. Also, two linear variable differential transformers, **285** and **286**, are used to provide a measure of the angular rotation of the drive housing through measuring the translation of the corresponding moving ends of linear actuators **283** and **284** with respect to the bases thereof. Only portions of linear variable differential transformers **285** and **286** can be seen in FIGS. 16 and 17. Linear variable differential transformer **285** corresponds to linear variable transformer **120** in FIGS. 11, **12** and 13 and linear variable differential transformer **286** is the substitute for linear variable differential transformer **155** in FIG. **13** used

with translation carriage **153**. Because of the otherwise similar construction and performance of wrist-like joints **102** and **280**, no further description will be provided here of joint **280** other than that hand-like structure **282** is supported on an output yoke, **287**, in wrist-like joint **280**.

Hand-like structure **282** is supported on output yoke **287** by a master support frame, **288**, at a master support base, **289**, therein that is fastened to yoke **287** with machine screws not shown. Support frame **288** is better seen in FIG. **18** where a first extension, **290**, extends from support base **289** to the right in that figure to thereafter curve around behind that base. Support frame **288** has a second extension, **291**, rotatably connected to support base **289** by a shouldered sleeve, **292**, fastened to base **289** by a machine screw, **293**. Extension **291** extends to the left in FIG. **18** from its rotary connection to base **289** and then curves around behind that base to be rotatably connected to a linear actuator, **294**, by a pivot pin, **295**, passing through the opposite sides of a yoke at the extreme end of the outer movable body of actuator **294** and through a hole through the end of second extension **291** positioned between those two sides.

The opposite, or base, end of linear actuator **294** is rotatably connected in a yoke, **296**, formed at the end of first extension **290** by a pivot pin, **297**, passing through the two sides of yoke **296** and the base end of actuator **294**. Thus, the outer movable body of actuator **294**, in being activated to travel back and forth with respect to the end thereof held in yoke **296**, forces second extension **291** to rotate clockwise and counterclockwise with respect to base support **289**. The degree of such rotation is measured by a linear differential variable transformer, **298**, fastened both to the base end and the outer body of linear actuator **294** to measure the distance one end has traveled with respect to the other. A machine spring is also formed at the base of linear actuator **294**, and a linear variable differential transformer not seen is provided thereacross to measure the elongation or contraction of that spring to thereby measure the force on actuator **294**.

Rotatably mounted to first extension **290** are a pair of clevises, **299** and **300**, these being rotatably connected by a corresponding pair of sleeve and machine screw combinations, **301** and **302**. Similarly, rotatably mounted to second extension **291** are a pair of clevises, **303** and **304**, again so connected by a corresponding pair of sleeve and machine screw combinations, **305** and **306**. Each of these clevises in each of these pairs thereof has the base end of a corresponding linear actuator rotatably mounted therein by a corresponding pivot pin as can be seen in FIG. **16**. Thus, clevis **299** is rotatably connected to a corresponding linear actuator, **307**. Similarly, clevis **300** is rotatably connected to a corresponding linear actuator, **308**. In the remaining pair of clevises connected to second extension **291**, clevis **303** is rotatably connected to a corresponding linear actuator, **309**, and clevis **304** is rotatably connected to a corresponding linear actuator, **310**.

Linear actuator **307** has provided at the extreme of the movable end thereof a ball, **311**, supported on a short pedestal as seen in FIG. **16**. Similarly, the extreme of the movable end of linear actuator **308** has provided thereat a further ball, **312**, on a short pedestal. In much the same manner, linear actuator **309** has a ball, **313**, supported on a short pedestal as the extreme of its movable end, as does linear actuator **310** in supporting a further ball, **314**.

Linear actuators **307** and **308** together rotatably support a digit capture base, **315**, at a yoke, **316**, formed at the bottom thereof as seen in FIGS. **16** and **17**. The arms of yoke **316** each have an opening therein having an interior surface of

which at least a portion follows a spherical surface. Ball 311 is captured in one of these openings by a capture plate, 317, also having an opening therein following in part a spherical surface, such that digit capture base 315 can rotate about ball 311. Ball 312 is captured in the remaining opening in the other arm of yoke 316 by a further capture plate, 318, also having a opening with the portion following a spherical surface so that base 315 can rotate about ball 312 also.

The remainder of digit capture base 315 extending upward in FIGS. 16 and 17 from yoke 316 is formed much like a portion of a hollow tube-like structure with portions of the tube wall omitted. Thus, there are two sidewalls, 319 and 320, in digit capture base 315 extending upward in FIGS. 16 and 17 from yoke 316 with a back bridge, 321, joining sidewalls 319 and 320 just above yoke 316 as is best seen in FIG. 17. Further up digit capture base 315 is a front bridge, 322, also joining sidewalls 319 and 320 with front bridge 322 flaring outward from those sidewalls to provide room for a portion of the index finger or digit of operator 11 within digit capture base 315 during use.

At the end of digit capture base 315 opposite that end thereof formed with yoke 316 there is rotatably connected a digit capture first extension, 323, with this rotatable connection being accomplished by a pair of pivot pins, 324. Again, a yoke, 325, is formed toward the bottom of digit capture first extension 323 to which the movable end of a linear actuator, 326, is rotatably attached by a pair of pivot pins, 327. The base end of linear actuator 326 is fastened in yoke 316 of digit capture base 315 by a further pair of pivot pins, 328. Thus, linear actuator 326 is capable of causing digit capture first extension 323 to rotate with respect to digit capture base 315 about pivot pins 324. Linear actuator 326 has a machined spring at the base end thereof over which is connected a linear variable differential transformer, 329, to measure the elongation and contraction of that spring to determine the force on actuator 326 which is to be nulled out by control arrangement 13 in operating that actuator. In addition, a further linear variable differential transformer, 330, is connected between the base and moveable ends of actuator 326 to determine the translation of the moveable end with respect to the base as an indication of the amount of rotation of digit capture first extension 323 with respect to digit capture base 315 provided by the captured index digit of operator 11 and actuator 326 in nulling out the force provided by that index digit.

Linear actuators 307 and 308 also each have machined springs at the ends thereof for determining forces on these actuators while positioned at the back of the right hand of operator 11 during use. Here, though, such forces can arise because of motions of the index digit of operator 11 that are other than rotary motions about a single axis because digit capture base 315 is not merely rotatably connected to another solid structure by pivot pins but is instead connected to linear actuators 307 and 308 using ball-and-socket connections thereby permitting rotations of base 315 about an entire array of axes. Linear actuator 307 has a linear variable differential transformer, 331, connected over its base machined spring to determine the force thereon introduced by movements of the index digit of operator 11 during use. Similarly, linear actuator 308 has a linear variable differential transformer, 332, connected over its base machined spring to determine the force thereon during use. Here too, the forces on these actuators must be nulled out by control arrangement 13 operating the corresponding actuator, and these forces may be unequal because of side-to-side motions of the index digit of operator 11 during use.

A further linear variable differential transformer, 333, is connected between the base and moveable ends of linear

actuator 307 to measure the translation between the ends thereof as an estimate of the rotation of digit capture base 315 about ball 311. In a like manner, another linear variable differential transformer, 334, is connected between the base and moveable ends of linear actuator 308 to measure the translation between the ends thereof as an estimate of the rotation of digit capture base 315 about ball 312.

Returning to digit capture first extension 323, this extension is also shaped as a tube-like structure with portions of the tube wall omitted. Thus, digit capture first extension 323 has a pair of sidewalls, 335 and 336, extending upward from yoke 325 with a back bridge, 337, joining sidewalls 335 and 336 together just above yoke 325. A front bridge, 338, also joins sidewalls 335 and 336 further up from yoke 325, and again flares outward from sidewalls 335 and 336 to provide room within digit capture first extension 323 for another portion of the index finger of operator 11 during use.

A further yoke, 339, located at the end of digit capture first extension 323 opposite the end with yoke 325, has a digit capture second extension, 340, rotatably connected to it by a pair of pivot pins, 341. Digit capture second extension 340 is formed similar to a thimble having the front portion of the thimble wall omitted. In view of no separate actuator having been provided to independently operate corresponding second gripping extension 223 in hand-like structure 104 in slave robot 10, which is instead operated with gearing actuated by linear actuator 218 to rotate with respect to first gripping extension 216, digit captdre second extension 340 has been allowed to rotate freely with respect to digit capture first extension 323. In these circumstances of no independent force being applied to rotate second gripping extension 223, there is no need for an actuatdr to be connected between digit capture second extension 340 and digit capture first extension 323 to null out forces introduced by the extreme end section of the index finger od digit of the right hand of operator 11 in digit capture second extension 340 as the basis for generating a force magnitude signal to operate an actuator in slave robot 10 for supplying such independent force to second gripping extension 223.

In a manner similar to linear actuators 307 and 308, linear actuators 309 and 310 together rotatably support a digit capture base, 345, at a yoke, 346, formed at the bottom thereof again as seen in FIGS. 16 and 17. The arms of yoke 346 each have an opening therein having an interior surface of which at least a portion follows a spherical surface. Ball 313 is captured in one of these openings by a capture plate, 347, also having an opening therein following in part a spherical surface, such that digit capture base 345 can rotate about ball 313. Ball 314 is captured in the remaining opening in the other arm of yoke 346 by a further capture plate, 348, also having a opening with the portion following a spherical surface so that base 345 can rotate about ball 314 also.

Here too, the remainder of digit capture base 345 extending upward in FIGS. 16 and 17 from yoke 346 is formed much like a portion of a hollow tube-like structure with portions of the tube wall omitted. Thus, there are two sidewalls, 349 and 350, in digit capture base 345 extending upward in FIGS. 16 and 17 from yoke 346 with a back bridge, 351, joining sidewalls 349 and 350 just above yoke 346 as is best seen in FIG. 17. Further up digit capture base 345 is a front bridge, 352, also joining sidewalls 349 and 350 with front bridge 352 flaring outward from those sidewalls to provide room for a portion of the middle finger or digit of operator 11 within digit capture base 345 during use.

At the end of digit capture base 345 opposite that end thereof formed with yoke 346 there is rotatably connected a

digit capture first extension, 353, with this rotatable connection being accomplished by a pair of pivot pins, 354. Again, a yoke, 355, is formed toward the bottom of digit capture first extension 353 to which the movable end of a linear actuator, 356, is rotatably attached by a pair of pivot pins, 357. The base end of linear actuator 356 is fastened in yoke 346 of digit capture base 345 by a further pair of pivot pins, 358. Thus, linear actuator 356 is capable of causing digit capture first extension 353 to rotate with respect to digit capture base 345 about pivot pins 354. Linear actuator 356 has a machined spring at the base end thereof over which is connected a linear variable differential transformer, 359, to measure the elongation and contraction of that spring to determine the force on actuator 356 which is to be nulled out by control arrangement 13 in operating that actuator. In addition, a further linear variable differential transformer, 360, is connected between the base and moveable ends of actuator 356 to determine the translation of the moveable end with respect to the base as an indication of the amount of rotation of digit capture first extension 353 with respect to digit capture base 345 provided by the captured middle digit of operator 11 and actuator 356 in nulling out the force provided by that middle digit.

Linear actuators 309 and 310 also each have machined springs at the ends thereof for determining forces on these actuators while positioned at the back of the right hand of operator 11 during use. Here, though, such forces can arise because of motions of the middle digit of operator 11 that are other than rotary motions about a single axis because digit capture base 345 is not merely rotatably connected to another solid structure by pivot pins but is instead connected to linear actuators 309 and 310 using ball-and-socket connections thereby permitting rotations of base 345 about an entire array of axes. Linear actuator 309 has a linear variable differential transformer, 361, connected over its base machined spring to determine the force thereon introduced by movements of the middle digit of operator 11 during use. Similarly, linear actuator 310 has a linear variable differential transformer, 362, connected over its base machined spring to determine the force thereon during use. Here too, the forces on these actuators must be nulled out by control arrangement 13 operating the corresponding actuator, and these forces may be unequal because of side-to-side motions of the middle digit of operator 11 during use.

A further linear variable differential transformer, 363, is connected between the base and moveable ends of linear actuator 309 to measure the translation between the ends thereof as an estimate of the rotation of digit capture base 345 about ball 313. In a like manner, another linear variable differential transformer, 364, is connected between the base and moveable ends of linear actuator 310 to measure the translation between the ends thereof as an estimate of the rotation of digit capture base 345 about ball 314.

Returning to digit capture first extension 353, this extension is again shaped as a tube-like structure with portions of the tube wall omitted. Thus, digit capture first extension 353 has a pair of sidewalls, 365 and 366, extending upward from yoke 355 with a back bridge, 367, joining sidewalls 365 and 366 together just above yoke 355. A front bridge, 368, also joins sidewalls 365 and 366 further up from yoke 355, and again flares outward from sidewalls 365 and 366 to provide room within base capture first extension 353 for another portion of the middle finger of operator 11 during use.

A further yoke, 369, at the end of digit capture first extension 353 opposite the end with yoke 355 has a digit capture second extension, 370, rotatably connected to it by a pair of pivot pins, 371. Digit capture second extension 370

is, like extension 340, formed similar to a thimble having the front portion of the thimble wall omitted. In view of no separate actuator having been provided to independently operate corresponding second gripping extension 231 in hand-like structure 104 in slave robot 10, which is instead operated with gearing actuated by linear actuator 227 to rotate with respect to first gripping extension 225, digit capture second extension 370 has been allowed to rotate freely with respect to digit capture first extension 353. Again, in these circumstances of no independent force being applied to rotate second gripping extension 231, there is no need for an actuator to be connected between digit capture second extension 370 and digit capture first extension 353 to null out forces introduced by the extreme end section of the middle finger or digit of the right hand of operator 11 in digit capture second extension 370 as the basis for generating a force magnitude signal to operate an actuator in slave robot 10 for supplying such independent force to second gripping extension 231.

An opposed digit capture bracket, 375, has a yoke, 376, formed at the lower end thereof in FIGS. 16 and 17, and a further yoke, 377, formed at the opposite, upper end thereof. A linear actuator, 378, is rotatably held by a pivot pin, 379, passing therethrough and through the sides of yoke 376. The movable end of actuator 378 is also rotatably connected by a further pivot pin unseen but used in a yoke, also unseen, that is formed as an inner yoke inside an outer yoke, 379, which is formed in an opposed digit capture base, 380, along with this unseen inner yoke. Opposed digit capture base 380 has its outer yoke 379 rotatably connected to yoke 377 of opposed digit capture base 375 by a pair of pivot pins, 381. Thus, linear actuator 378, positioned during use against the side of the right hand of operator 11 below the thumb, is operated by control arrangement 13 to null any force introduced thereon by the thumb of operator 11 in causing opposed digit capture base 380 to rotate with respect to opposed digit capture bracket 375. The extent of any such rotation is again estimated by the translation between the base and moving ends of actuator 378 as measured by a linear variable differential transformer, 382, connected therebetween. Any force introduced on this actuator is again measured by the use of a machined spring in the base end thereof with its elongation and contraction measured by a further linear variable differential transformer, 383, fastened to the base end of actuator 378.

Opposed digit capture base 380 has a further yoke, 384, formed at the opposite end thereof. An opposed digit capture extension, 385, has a yoke, 386, formed at the lower end thereof, and this yoke 386 is rotatably connected to yoke 384 of opposed digit capture base 380 by a further pair of pivot pins, 387. Outer yoke 379 at the lower end of opposed digit capture base 380, and the unseen inner yoke therein rotatably connected to the movable end of linear actuator 378, are formed on the lower ends of a pair of side walls, 388 and 389, which extend upward to form upper yoke 384 in that base. Thus, this base again is formed as a tube-like structure with portions of the tube wall omitted. A back bridge, 390, joins side walls 388 and 389 just above outer yoke 379. A front bridge, 391, joins side walls 388 and 389 further up base 380 closer to yoke 384.

Opposed digit capture extension 385 again is formed much like a thimble with a portion of the thimble wall omitted. Here too, since no separate actuator has been provided to independently operate corresponding opposed gripping extension 238' in hand-like structure 104 of slave robot 10 to rotate same with respect to first opposed gripping extension 238 (gearing actuated by linear actuator 236 being

used instead), opposed digit capture extension **385** has been allowed to rotate freely with respect to opposed digit capture base **380**. Since no independent force is being applied to rotate opposed gripping extension **238'**, there is no need for an actuator to be connected between opposed digit capture base **380** and opposed digit capture extension **385** to null out forces introduced by the extreme end section of the thumb of the right hand of operator **11** in opposed digit capture extension **385** as a basis for generating a force magnitude signal to operate an actuator in slave robot **10** for supplying such independent force to opposed gripping extension **238'**.

Measuring the results of circumferential motion of the thumb of the right hand of operator **11** during use is provided for by two further linear actuators, **393** and **394**, which extend and retract at approximately right angles to one another during use in nulling out the forces introduced thereon by the thumb of that operator. Actuator **393**, shown exploded away from the rest of hand-like structure **282** in FIG. **16**, has a machined spring, **395**, in the base thereof and has this base end rotatably connected by a pivot pin, **396**, in a clevis, **397**, which is rotatably connected in an opening, **398**, in a support bar, **399**, in master frame **288** which is attached to support base **289** therein as seen in FIG. **18**. The movable end of actuator **393** has a ball at its extreme end on a base, or short pedestal, which is captured in an opening provided in part by opposed digit capture bracket **375** to be described below. A linear variable differential transformer, **400**, measures translation between the base and movable ends of actuator **393**, and a further linear variable differential transformer, **401**, measures elongation and compaction of machined spring **395**.

Linear actuator **394**, better seen in FIG. 17, has a machined spring, **402**, in the base thereof and has this base end rotatably connected by a pivot pin, **403**, in a clevis, **404**, which is rotatably connected in an opening, **405**, in first frame extension **290** of support frame **288** seen in FIG. 18. The movable end of actuator **394** is rotatably connected by a pivot pin, **406**, in a clevis, **407**, which is rotatably connected into a portion of opposed digit capture bracket **375** to be described below. A linear variable differential transformer, **408**, measures translation between the base and movable ends of actuator **394**, and a further linear variable differential transformer, **409**, measures the elongation and compaction of machined spring **402**.

Opposed digit capture bracket **375** has a first circumferential motion arm, **410**, rigidly connected therein in which clevis **407** is rotatably connected. Bracket **375** also has a second circumferential motion arm, **411**, rigidly connected therein on the opposite side thereof from arm **410**, and arm **411** has an opening therein at its extreme end that has an interior surface of which at least a part follows a portion of a spherical surface to allow the ball on the short pedestal at the extreme of the movable end of linear actuator **393** to be captured and rotated therein by a capture plate, **412**. Capture plate also has an opening therein with an interior surface at least a part of which follows a portion of the spherical surface.

Circumferential motions of the right thumb of operator **11** will lead to introducing forces on linear actuators **393** and **394** which will be sensed by the corresponding force sensors formed of machined spring **395** and linear variable differential transformer **401** for actuator **393**, and of machined spring **402** which linear variable differential transformer **409** for actuators **394**. These signals will be used by control arrangement **13** to provide operating signals to linear actuators **393** and **394** to null out the sensed forces thereon as a basis for generating signals by control arrangement **13** for

operating linear actuators **243** and **244** in hand-like structure **104** of slave robot **10**.

A support plate, **415**, with a VELCRO® hook tape mounted thereon is affixed to master support base **289** of master support frame **288** by machine screws, **416**, (but shown exploded away therefrom in FIG. **16**). Operator **11** has his right hand during use inserted in a glove, **417**, seen in FIG. **19**. The back of glove **417** has a VELCRO® loop tape, **418**, mounted thereon but shown only in dotted line form in FIG. **19**. Thus, when operator **11** has his right hand inserted in glove **417** with **1)** his thumb positioned in opposed digit capture base **380** and opposed digit capture extension **385**, ii) his index finger positioned in digit capture base **315**, digit capture first extension **323** and digit capture second extension **340**, and iii) his middle finger positioned in digit capture base **345**, digit capture first extension **353** and digit capture second extension **370**, the VELCRO® hook tape mounted on support **415** will be removably fastened to VELCRO® loop tape **418** mounted on glove **417** to the right hand of operator **11** in this position in master hand-like structure **282**.

Hence, motions of the thumb, index finger or middle finger of the right hand of operator **11** will cause similar motions of the corresponding mechanical apparatuses in which they are positioned in master hand-like structure **282**, rather than these corresponding apparatuses being only partially moved due slippings of master hand-like structure **282** about the hand of operator **11** during such motions in the absence of such a back of the hand fastening arrangement. As a result of the good correlation between the motions of the thumb, index finger or middle finger of the right hand of operator **11** initiated by that operator and the resulting motions of the corresponding mechanical apparatuses in which they are positioned in master hand-like structure **282**, the forces from these initiated motions leading to the mechanical apparatus motions will be fully nulled out by control arrangement **13** resulting in accurate signals being sent by control arrangement **13** to faithfully direct corresponding motions of corresponding apparatuses in slave hand-like structure **104**.

Glove **417** has two further VELCRO® hook tapes portions, **419**, provided thereon in the portion thereof covering the palm of the right hand of operator **11**. Portions **419** are for removably fastening a tactile actuator mount, **420**, to that palm portion of glove **417** at two corresponding VELCRO® loop tape portions, **421**, on that mount seen only in dotted line form in FIG. 19. Mount **420** supports a group of electrical solenoid actuators, **422**, protruding therethrough which are held against the palm portion of glove **417** with that mount fastened to that glove as described. Mount **420** along with actuators **422** form one of tactile force actuators **18** used for applying forces or pressure during operation to the palm of the right hand of operator **11** in proportion to the forces sensed by force sensing pads **270** on cover cushion **271** of hand-like structure **104** in such operation under the control of control arrangement **13**.

Others of tactile force actuators **18** seen in FIGS. 16 and 17 on the various bases and extensions shown there of hand-like structure **282** also apply forces or pressure to the portions of the right hand of operator **11** against which they are adjacent in proportion to the forces sensed on corresponding ones of sensing pads **270** of hand-like structure **104** also under the control of control arrangement **13**. These tactile force actuators, however, rather than being electrically operated solenoids, are each a group of electrically operated hammers or forcing arms as seen in more detail in the partially exploded view of FIG. **20**. There, a base block,

423, supports on its bottom the ends of nine resilient metal forcing arms, 424, which have the ends thereof opposite the supported ends turned upward at a ninety degree angle and covered with end caps, 425.

Each of metal forcing arms 424 at a distance from block 423 has an actuator wire, 426, fastened thereto through it being woven through three openings provided in that arm at that location, the opposite ends of wires 426 being held in slots in the top of block 423. Wires 426 are each formed of a shape-memory alloy which contract proportionally to the heating thereof which is provided by supplying a corresponding electrical current therethrough. To this end, electrical lead wires, 427, are provided to block 423 to connect to the supported ends of forcing arms 424 and the ends of wires 426 embedded in the slots of block 423 as can be seen in the cross section view shown in FIG. 21.

A touchboard, 428, has holes therethrough to accommodate end caps 425 and is fastened to block 423. Contraction of wires 426 forces forcing arms 424 upward to force end caps 425 outward through the holes in touchboard 428 and against the adjacent portions of glove 417 and the corresponding portions of the right hand of operator 11. The outward extent reached by these end caps, and so the tactile force or pressure applied to operator 11, is set by control arrangement 13 based on the amount of force sensed by the corresponding sensing pad 270 in hand-like structure 104.

Touchboard 428 is, in turn, fastened to a housing, 429, for enclosing and protecting the actuator. Touchboard 428, case 429 and arms 424 can all be formed with appropriate curvature therein to accommodate having the glove facing surface thereof maintain the adjacent surface curvature therearound when mounted in openings in the curved surfaces of the various bases and extensions of hand-like structure 282.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. An articulated manipulating system for mounting on a base in a robotic manipulator and capable of engaging selected objects, said system comprising:

a support frame having a base support for mounting on said base with said base support having a first frame extension so as to extend therefrom in a first direction and a second frame extension rotatable connected to said base support and extending therefrom in a second direction at an angle to said first direction;

a first effector base rotatably connected to said first frame extension so as to be rotatable with respect thereto in plural different directions;

a second effector base rotatable connected to said second frame extension so as to be rotatable with respect thereto in plural different directions;

first pair of base linear actuators each having an end thereof rotatably connected to said first frame extension at corresponding extension connection locations thereon, and each having that opposite end thereof rotatably connected to said first effector base at corresponding effector connection locations thereon so that any substantial differentials in movement of these actuators cause corresponding substantial motions of said first effector base towards a corresponding one of said extension connection locations and so that substantial common movements of these actuators causes substantial motions of said first said effector toward or away from both of said extension connection locations; and

a second pair of base linear actuators each having an end thereof rotatable connected to said second frame extension at corresponding extension connection locations thereon, and each having that opposite end thereof rotatably connected to said second effector base at corresponding effector connections locations thereon.

2. The apparatus of claim 1 wherein said first effector base is rotatably connected to said first frame extension by there being a first pedestal extending from said first frame extension in a direction at an angle with respect to said first direction and substantially away from said base arrangement and having a first partial spherical support mounted on said first pedestal having an outer surface substantially shaped at least in part as a portion of a spherical surface, said first effector base having a first capture opening at one end thereof with an interior surface substantially shaped at least in part as a portion of a spherical surface in which said first partial spherical support is positioned, said first pair of base linear actuators each having an end thereof rotatably connected to said first frame extension on either side of said first pedestal, and each having that opposite end thereof rotatably connected to said first effector base on opposite sides of said first capture opening.

3. The apparatus of claim 1 further comprising a first gripping extension rotatably connected to said first effector base and an extension linear actuator having one end thereof rotatably connected to said first effector base adjacent where said first frame extension is rotatably connected thereto, and that opposite end thereof rotatably connected to said first gripping extension adjacent to where said first gripping extension is rotatably connected to said first effector base.

4. The apparatus of claim 1 wherein said support frame has a subextension extending in a subextension direction at an angle to said first direction and said support frame has a support frame extension extending in a support direction at an angle to said first direction, and further comprising:

an opposed effector base rotatably connected to said subextension so as to be rotatable with respect thereto in orthogonal directions; and

a pair of lateral linear actuators each having an end rotatably connected to said opposed effector base and one of said pair having that opposite end thereof rotatably connected to said support frame extension, and that one remaining having that opposite end thereof rotatably connected to said first frame extension.

5. An articulated manipulating system for mounting on a base in a robotic manipulator and capable of engaging selected objects, said system comprising:

a support frame having a base support with a first frame extension so as to extend therefrom in a first direction, a base arrangement for mounting on said base comprising an output effector affixed to said base support, said output effector being rotatably mounted in a drive housing, said drive housing having a pair of housing sectorial frames affixed thereto, each having a bearing race following a circular arc therein for holding corresponding ball bearings against a corresponding bearing race following a circular arc in a corresponding one of a pair of housing sectorial mounts affixed to a support standard to result in said drive housing being rotatably connected to said support standard;

a first effector base rotatably connected to said first frame extension so as to be rotatable with respect thereto in plural different directions; and

a first pair of base linear actuators each having an end thereof rotatable connected to said first frame extension at corresponding extension connection locations thereon, and each having that opposite end thereof rotatably connected to said first effector base at corresponding effector connection locations thereon so that any substantial differentials in movement of these actuators cause corresponding substantial motions of said first effector base towards a corresponding one of said extension connection locations and so that substantial common movements of these actuators causes substantial motions of said first said effector toward or away from both of said extension connection locations.

6. The apparatus of claim 2 wherein each of said first effector base linear actuators has said end thereof rotatably connected to said first effector base so as to have said first effector base be rotatable with respect thereto in orthogonal directions.

7. The apparatus of claim 3 further comprising a second gripping extension rotatably connected to said first gripping extension at an end thereof opposite that to which said extension linear actuator is connected.

8. The apparatus of claim 1 wherein those ends of said first and second frame extensions away from said base support are directed sufficiently toward one another to permit connecting a relative motion linear actuator therebetween to permit causing said second frame extension to be rotated about said rotatable connection thereof to said base support.

9. The apparatus of claim 1 wherein said second effector base is rotatably connected to said second frame extension by there being a pedestal extending from said second frame extension in a direction at an angle with respect to said second direction and substantially away from said base arrangement and having a partial spherical support mounted on said pedestal having an outer surface substantially shaped as a portion of a spherical surface, said second effector base having a capture opening at one end thereof with an interior surface substantially shaped as at least a portion of a spherical surface in which said partial spherical support is positioned, said second pair of base linear actuators each having an end thereof rotatably connected to said second frame extension on either side of said pedestal, and each having that opposite end thereof rotatably connected to said second effector base on opposite sides of said capture opening.

10. The apparatus of claim 4 further comprising an opposed gripping extension rotatably connected to said opposed effector base and an opposed extension linear actuator having one end thereof rotatably connected to said opposed effector base adjacent where said subextension is rotatably connected thereto, and that opposite end thereof rotatably connected to said opposed gripping extension adjacent to where said opposed gripping extension is rotatably connected to said opposed base effector.

11. The apparatus of claim 5 wherein said output effector has a housed gear sector affixed thereto engaged with a housed drive gear on an output shaft of a housed drive motor supported in said drive housing, and with one of said pair of housing sectorial frames affixed to said drive housing having a housing drive gear sector affixed thereto which is engaged with a housing drive gear on an output shaft of a housing drive motor supported by said support tube.

12. The apparatus of claim 6 further comprising said first effector base linear actuators each having force sensors therein capable measuring forces thereon.

13. The apparatus of claim 6 further comprising said first effector base linear actuators each having relative translation sensors thereon capable measuring relative translations between ends thereof.

14. The apparatus of claim 1 wherein said first pair of base linear actuators are rotatably connected to said first effector base as aforesaid so as to be also on a further common side thereof.

15. The apparatus of claim 14 wherein said first pair of base linear actuators are rotatably connected to said first frame extension as aforesaid on either side of where said first effector base is rotatably connected thereto.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,967,580

DATED : OCTOBER 19, 1999

INVENTOR(S) : MARK E. ROSHEIM

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 27, line 47, delete "rotatable", insert --rotatably--

Col. 27, line 53, delete "rotatable", insert --rotatably--

Signed and Sealed this

Twenty-fifth Day of July, 2000

Attest:

Q. TODD DICKINSON

Attesting Officer

Director of Patents and Trademarks

US006658962B1

(12) **United States Patent**
Rosheim

(10) **Patent No.:** **US 6,658,962 B1**
(45) **Date of Patent:** **Dec. 9, 2003**

(54) **ROBOTIC MANIPULATOR**

(75) Inventor: **Mark E. Rosheim**, St. Paul, MN (US)

(73) Assignee: **Ross-Hime Designs, Incorporated**, Minneapolis, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/284,926**

(22) Filed: **Oct. 31, 2002**

Related U.S. Application Data

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(51) **Int. Cl.**[7] **B25J 17/02**

(52) **U.S. Cl.** **74/490.05**; 901/16; 901/26; 901/28

(58) **Field of Search** 74/490.01, 490.03, 74/490.05, 490.06; 901/15, 16, 23, 25, 26, 28

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(57) **ABSTRACT**

A controlled relative motion system having first and second support structures with a controlled output position joint connecting them, and with similar joints on these support structures. One joint is coupled to another controlled relative motion system having an output carrier rotatable in two perpendicular directions through the use of gears therein. This output carrier supports two articulated manipulating systems of which one has a single axis rotatable subbase supporting a rotatable gripping extension, and the other has a shackle connected to a base effector which shackle is supported on a fixed pedestal and another shackle connected to a base effector which shackle is supported on a moveable pedestal.

22 Claims, 15 Drawing Sheets

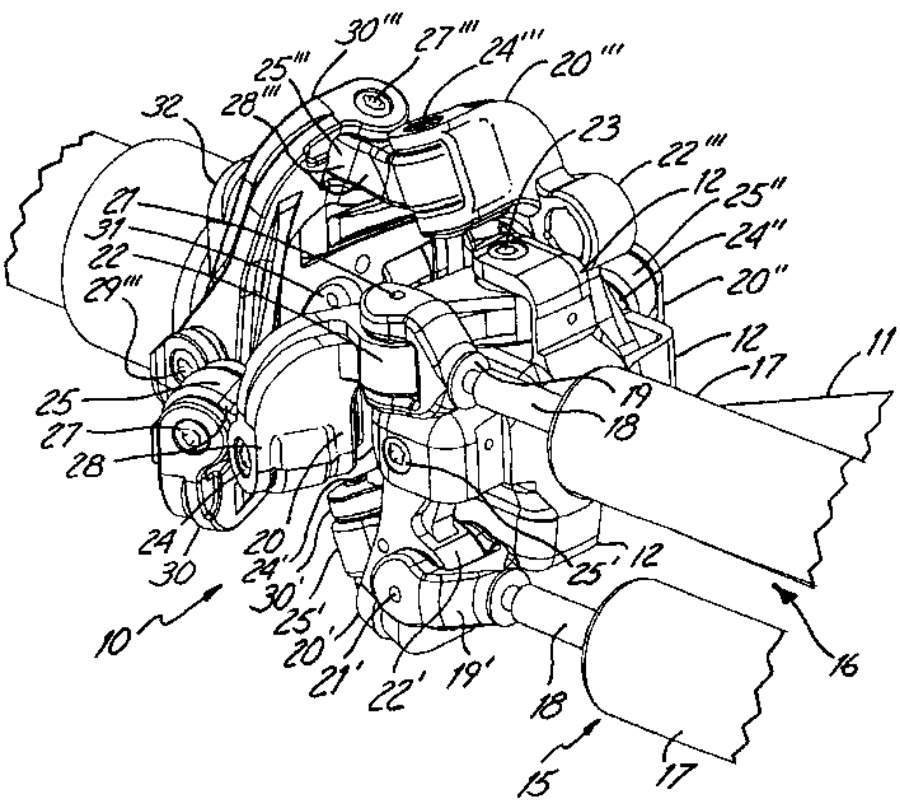
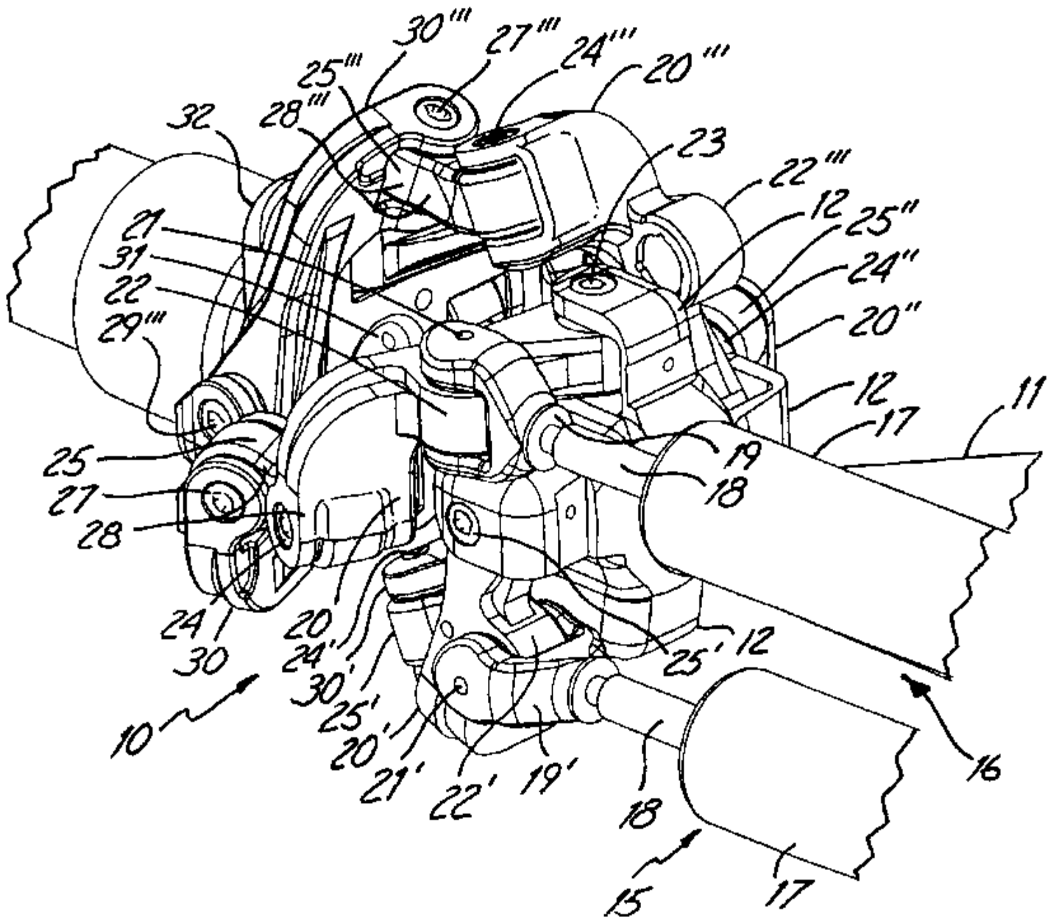


EXHIBIT 2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18
15
17

Fig. 1

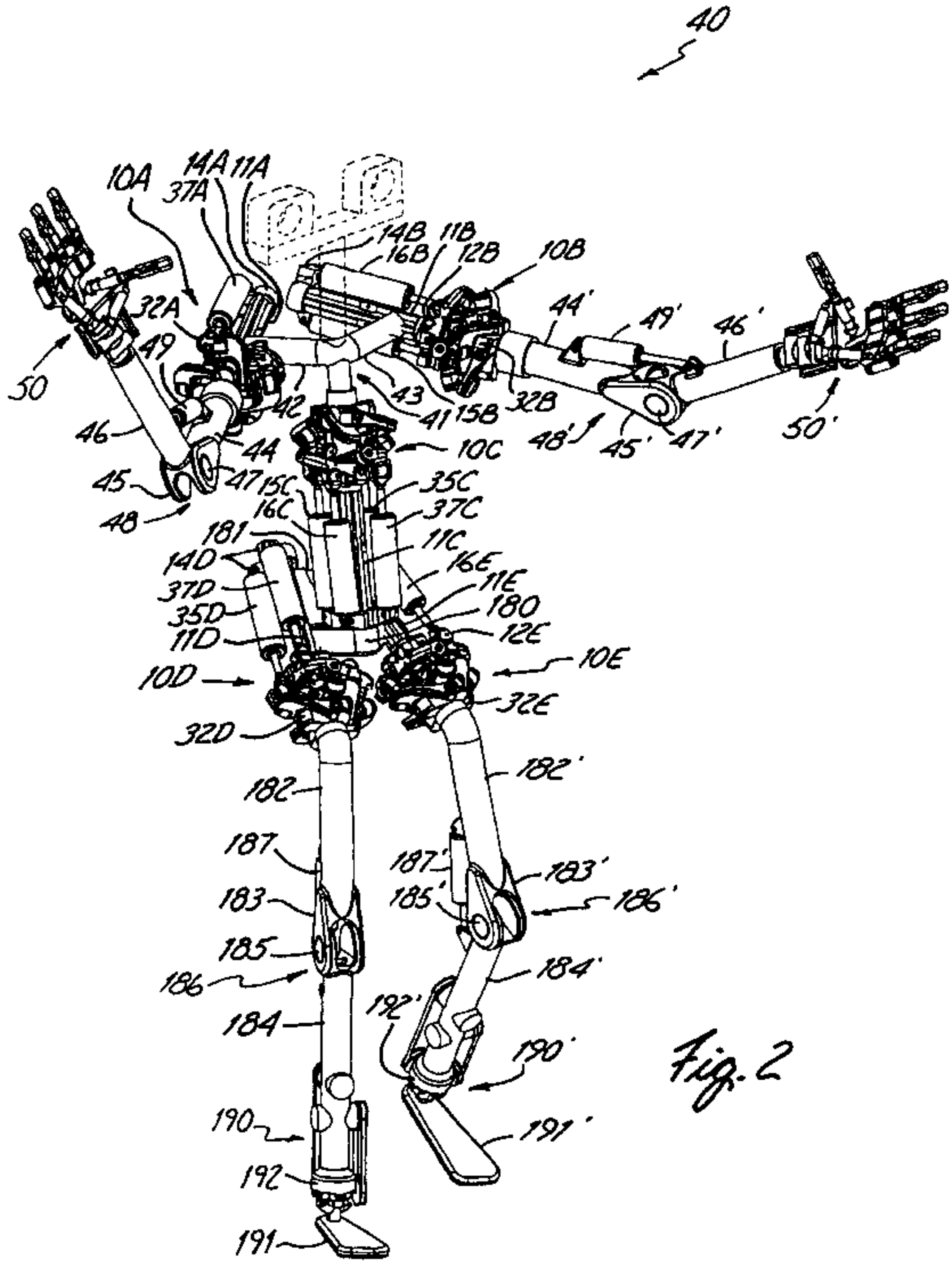

40
10A
14A
11A
37A
14B
11B
16B
12B
10B
32A
44'
49'
46'
49
50
43
42
41
15B
32B
46
44
10C
48'
45'
47'
50'
45
47
15C
35C
48
16C
37C
181
11C
14D
16E
37D
11E
35D
180
11D
12E
10E
10D
32E
32D
182
182'
187
187'
183'
183
185'
186'
185
184'
186
192'
184
190'
190
191'
192
191

Fig. 2

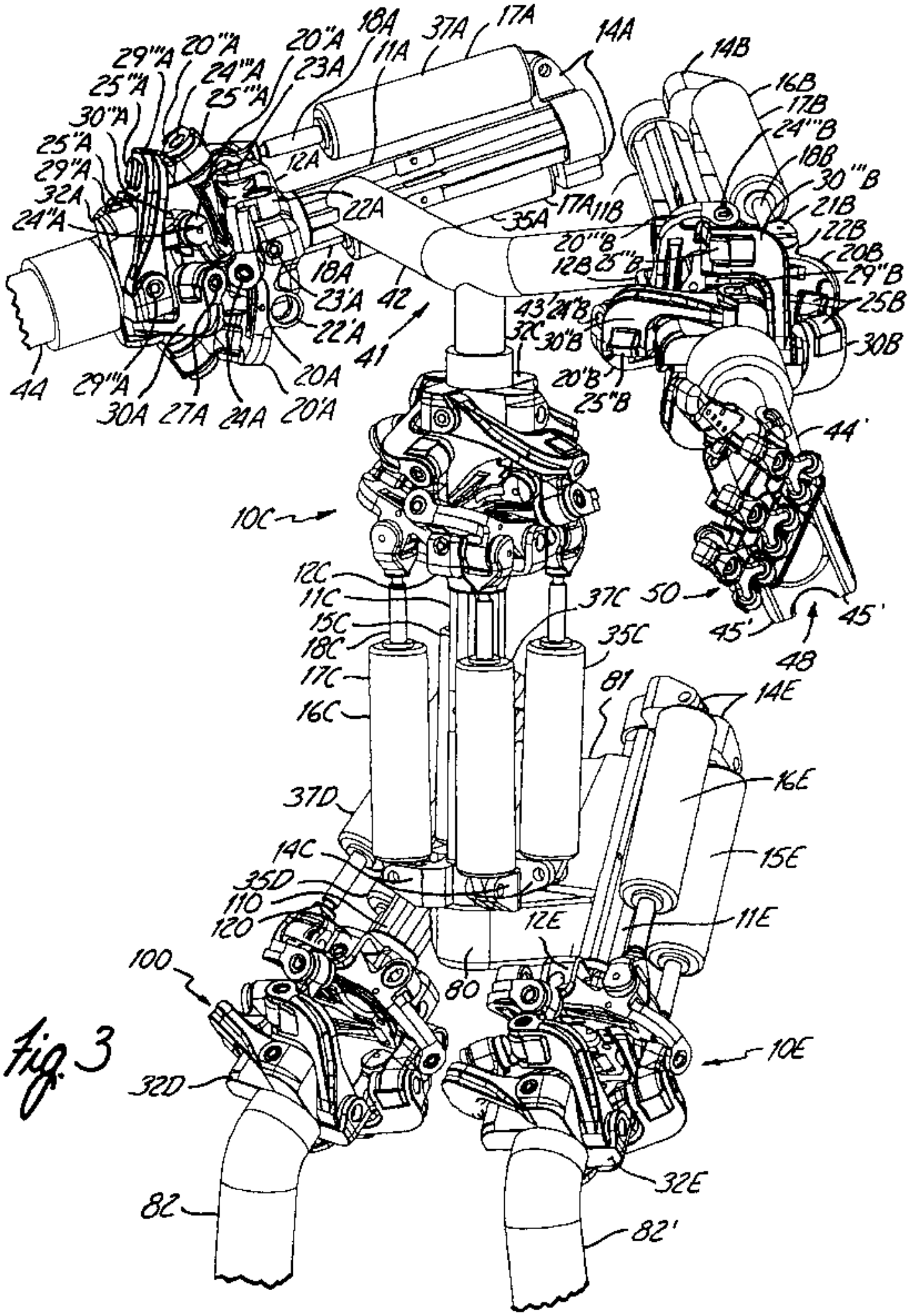
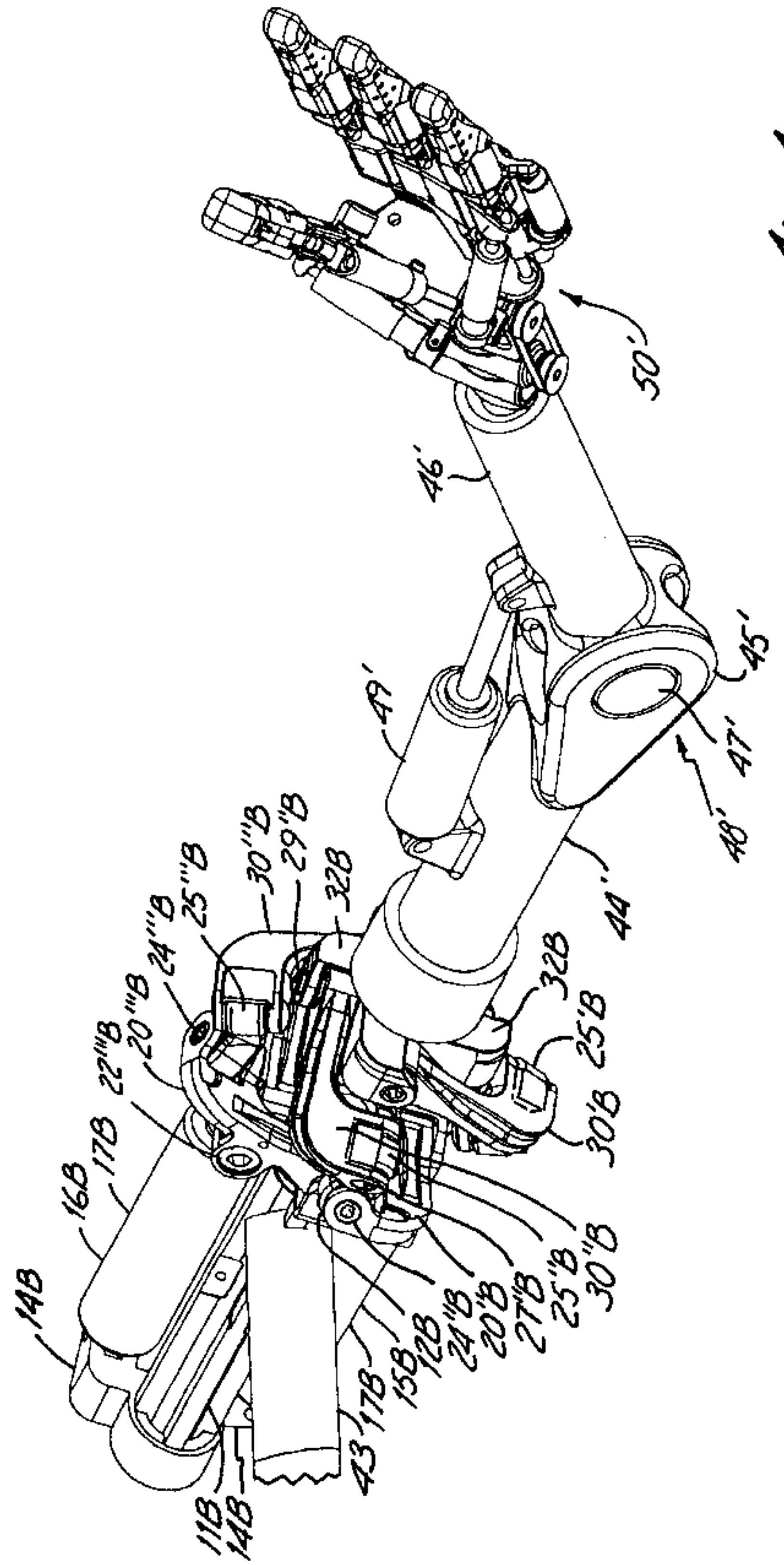


Fig. 3



50'
46'
45'
47'
48'
49'
44'
32B
29"B
30'"B
25"B
24'"B
20'"B
22'"B
17B
16B
14B
25'B
30'B
30"B
25"B
27'B
20'B
24"B
12B
15B
17B
43
11B
14B

Fig. 4

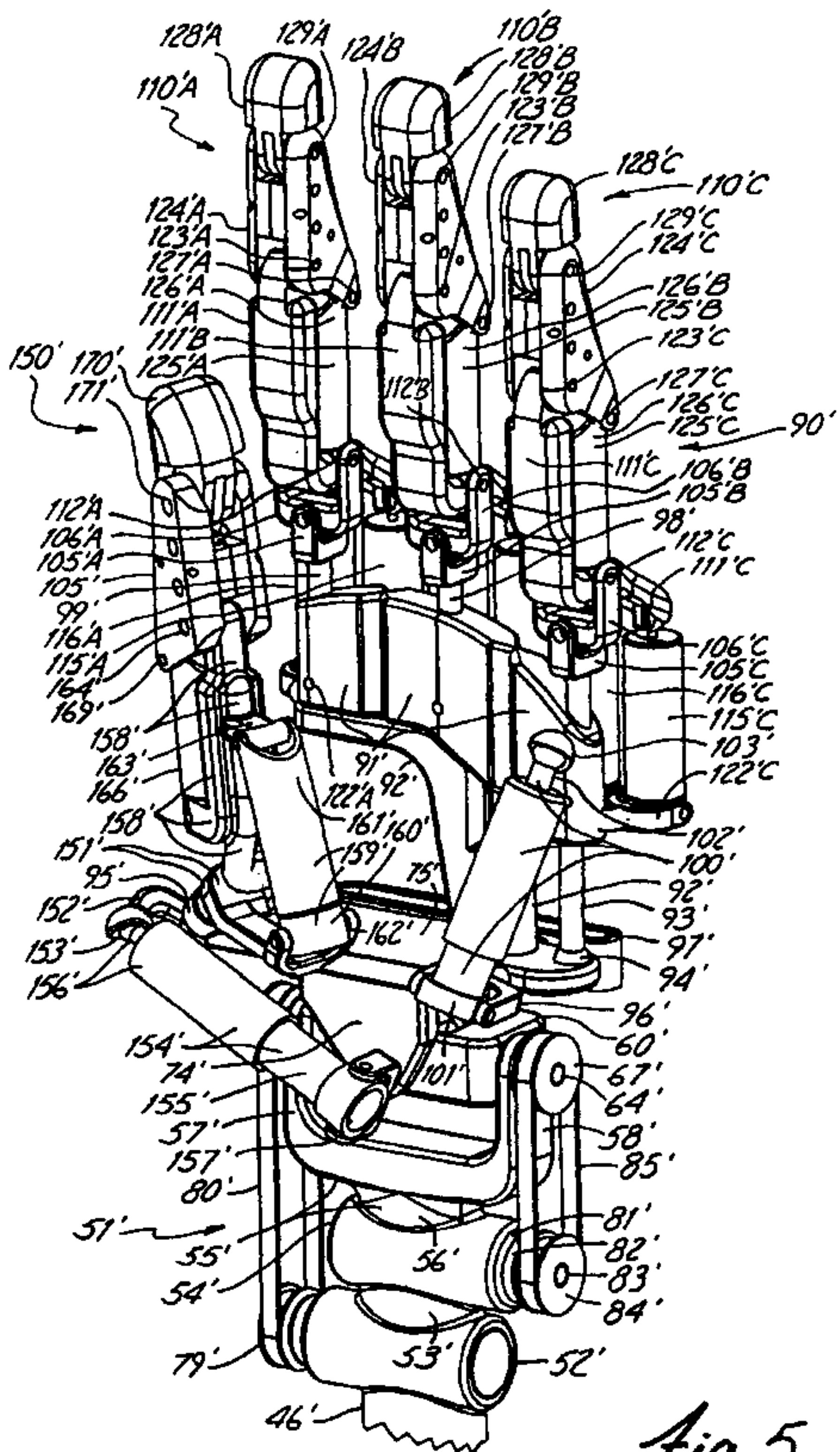

128'A
129'A
124'B
110'B
128'B
129'B
123'B
127'B
110'A
128'C
110'C
129'C
124'C
124'A
123'A
127'A
126'A
111'A
111'B
125'A
126'B
125'B
123'C
150'
170'
171'
112'B
127'C
126'C
125'C
90'
111'C
106'B
105'B
112'A
106'A
105'A
105'
99'
116'A
115'A
164'
169'
98'
112'C
111'C
106'C
105'C
116'C
115'C
103'
122'C
158'
163'
166'
158'
91'
92'
122'A
161'
160'
151'
95'
152'
153'
156'
159'
75'
162'
102'
100'
92'
93'
97'
94'
96'
60'
67'
64'
154'
74'
155'
57'
157'
80'
101'
58'
85'
51'
55'
54'
56'
81'
82'
83'
84'
79'
53'
52'
46'

Fig. 5

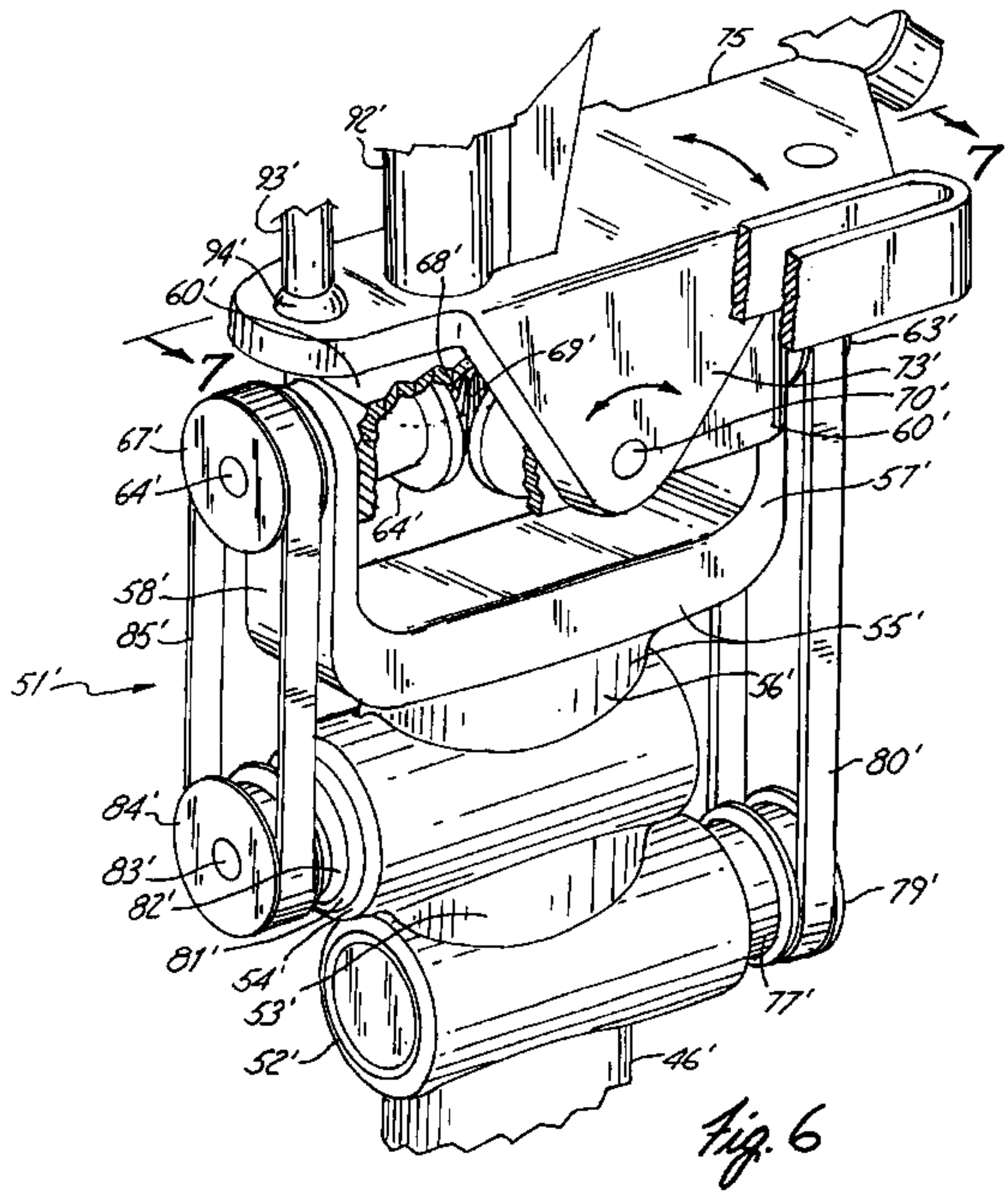

75
92'
93'
94'
60'
68'
7
69'
63'
73'
70'
60'
67'
64'
64'
57'
58'
85'
55'
51'
56'
80'
84'
83'
82'
79'
81'
54'
53'
77'
52'
46'

Fig. 6

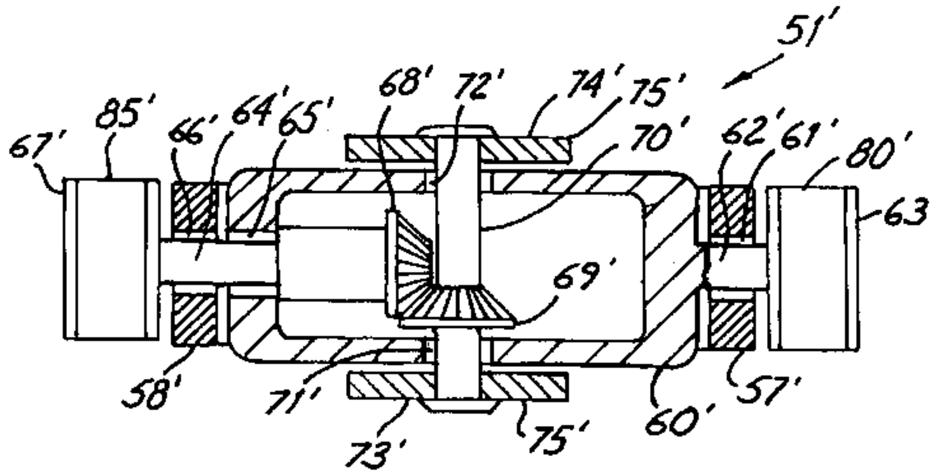
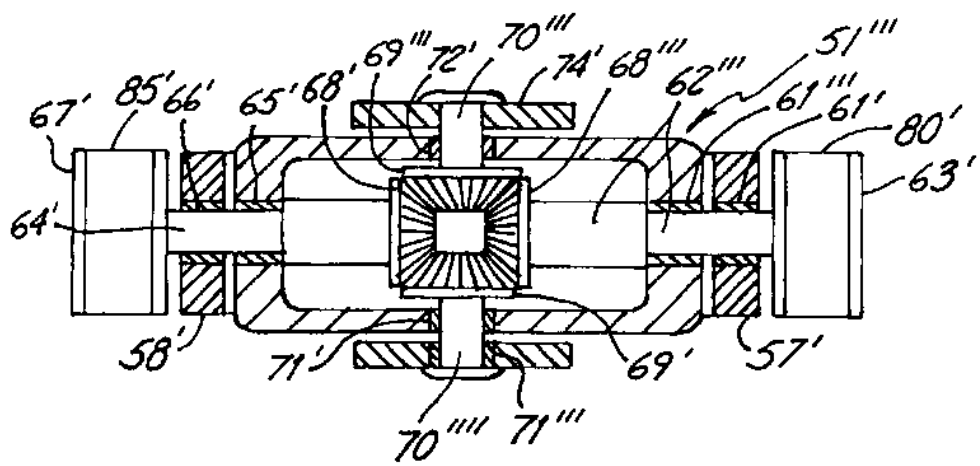

51'
68'
72'
74'
75'
85'
64'
65'
66'
67'
70'
62'
61'
80'
63'
69'
58'
71'
57'
60'
75'
73'

Fig. 7A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70'''
69'''
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74'
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67'
85'
66'
65'
68'
62'''
61'''
61'
80'
63'
64'
58'
71'
69'
57'
70''''
71'''

Fig. 7B

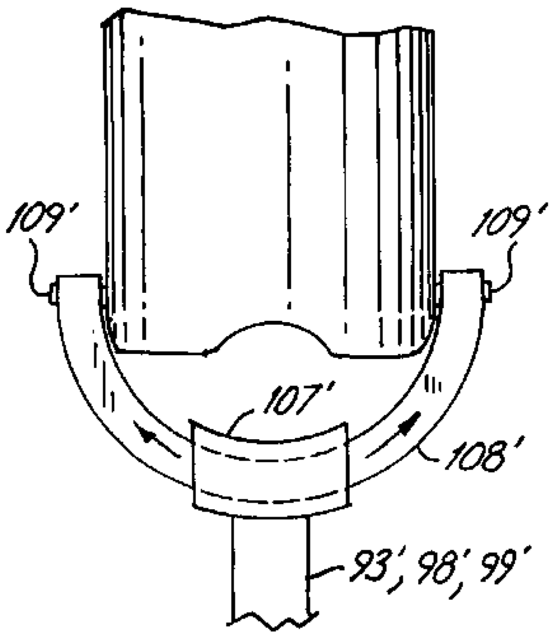


Fig. 8

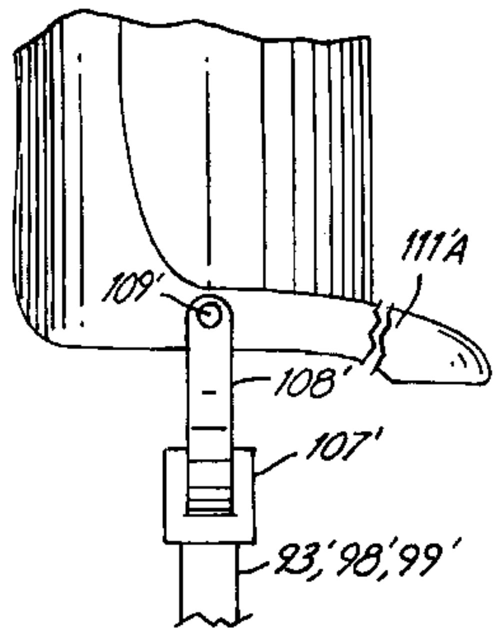
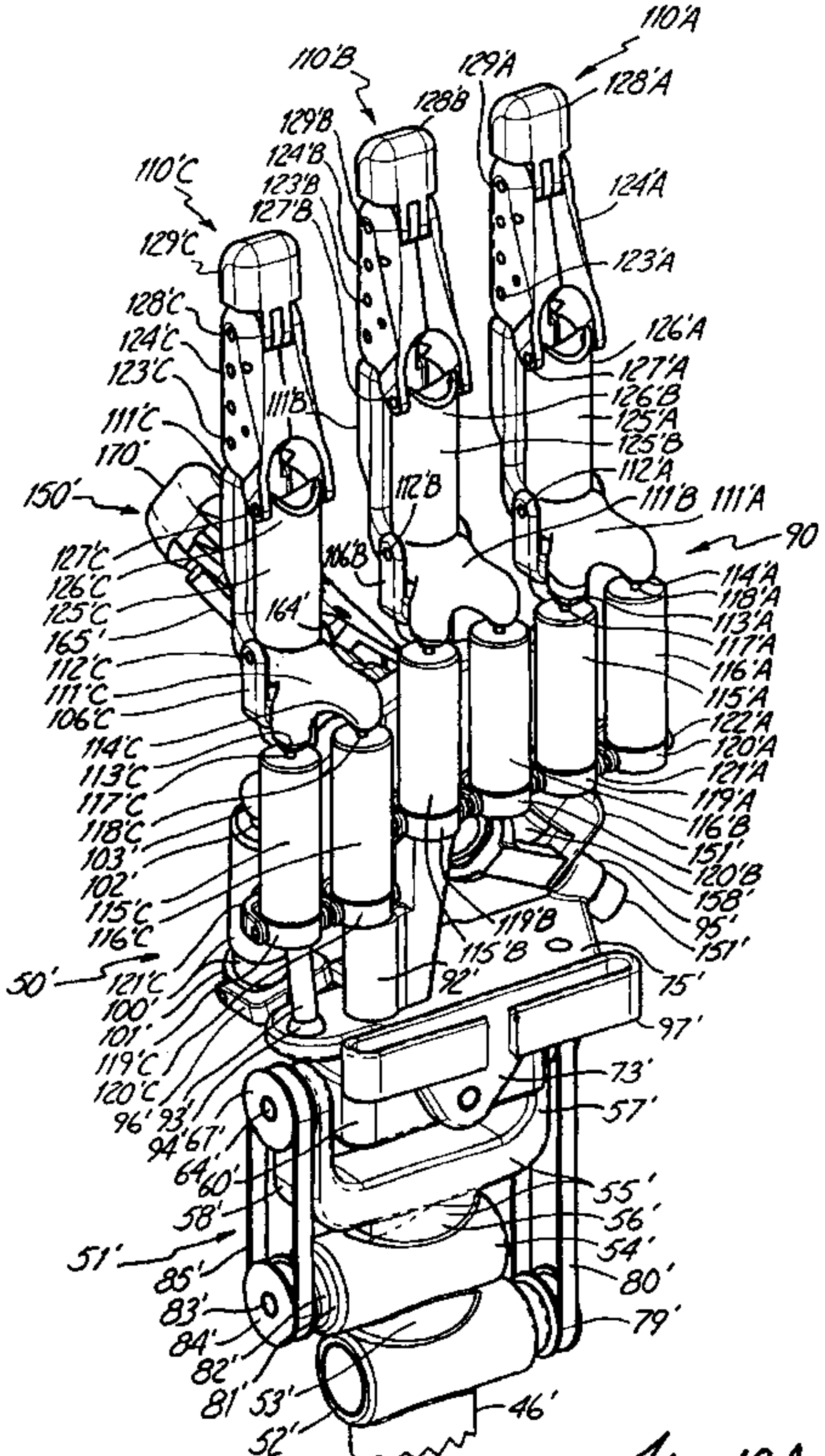


Fig. 9



110'A
110'B
129'A
128'A
128'B
129'B
124'B
123'B
127'B
110'C
124'A
129'C
123'A
128'C
126'A
124'C
127'A
123'C
126'B
111'B
125'A
111'C
125'B
170'
112'A
112'B
111'B
111'A
150'
90'
127'C
106'B
114'A
126'C
118'A
125'C
164'
113'A
165'
117'A
112'C
116'A
111'C
115'A
106'C
122'A
114'C
120'A
113'C
121'A
117'C
119'A
118'C
116'B
103'
151'
102'
120'B
115'C
119'B
158'
116'C
95'
115'B
151'
50'
121'C
92'
75'
100'
97'
101'
119'C
73'
120'C
96'
93'
57'
94'
67'
64'
60'
55'
58'
56'
54'
51'
85'
80'
83'
79'
84'
82'
81'
53'
46'
52'

Fig. 10A

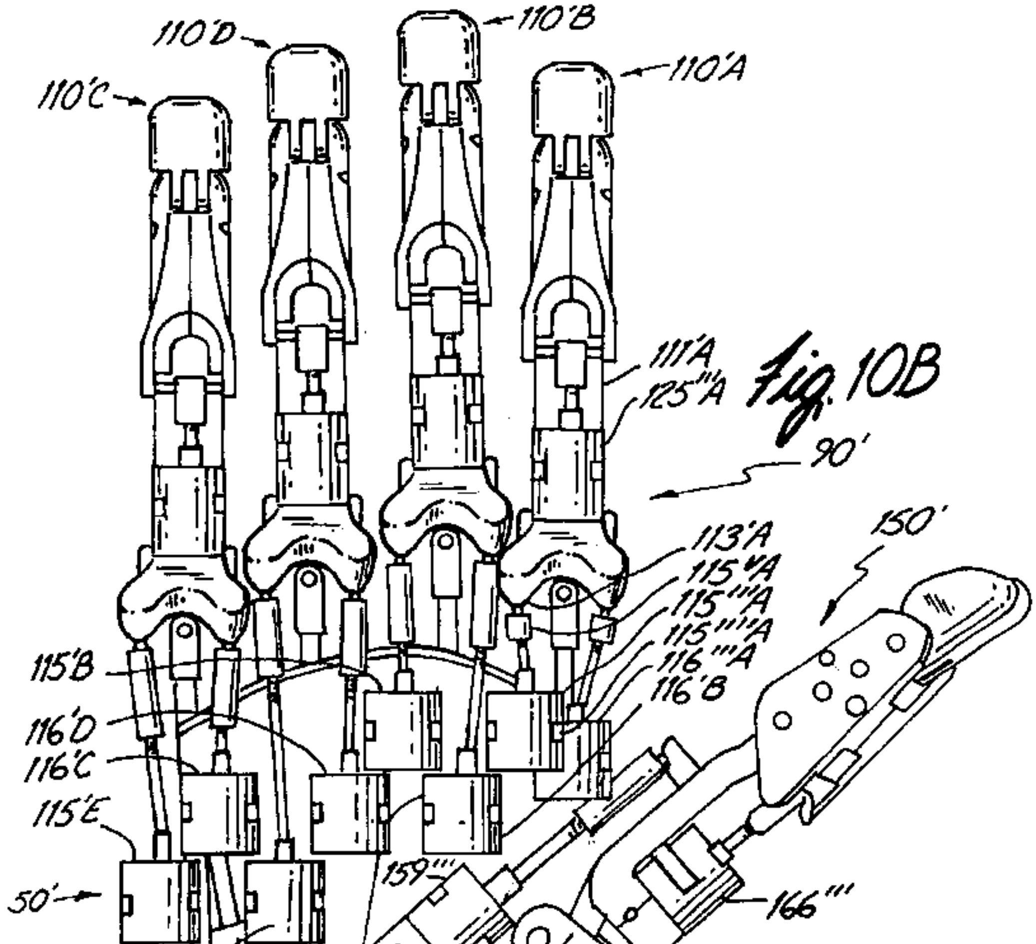


Fig. 10B

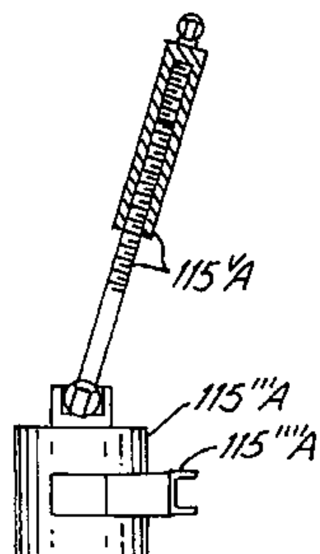
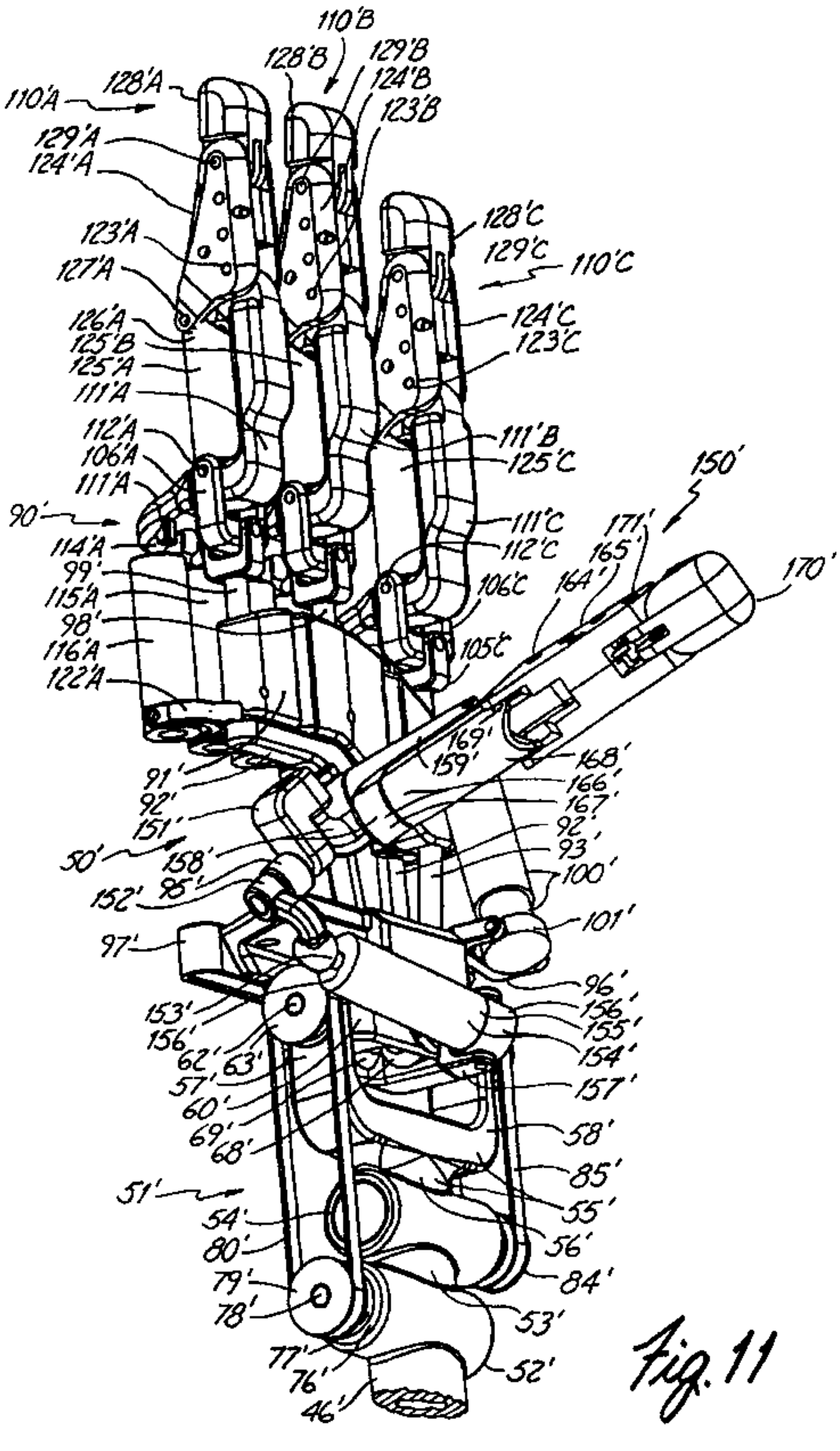


Fig. 10C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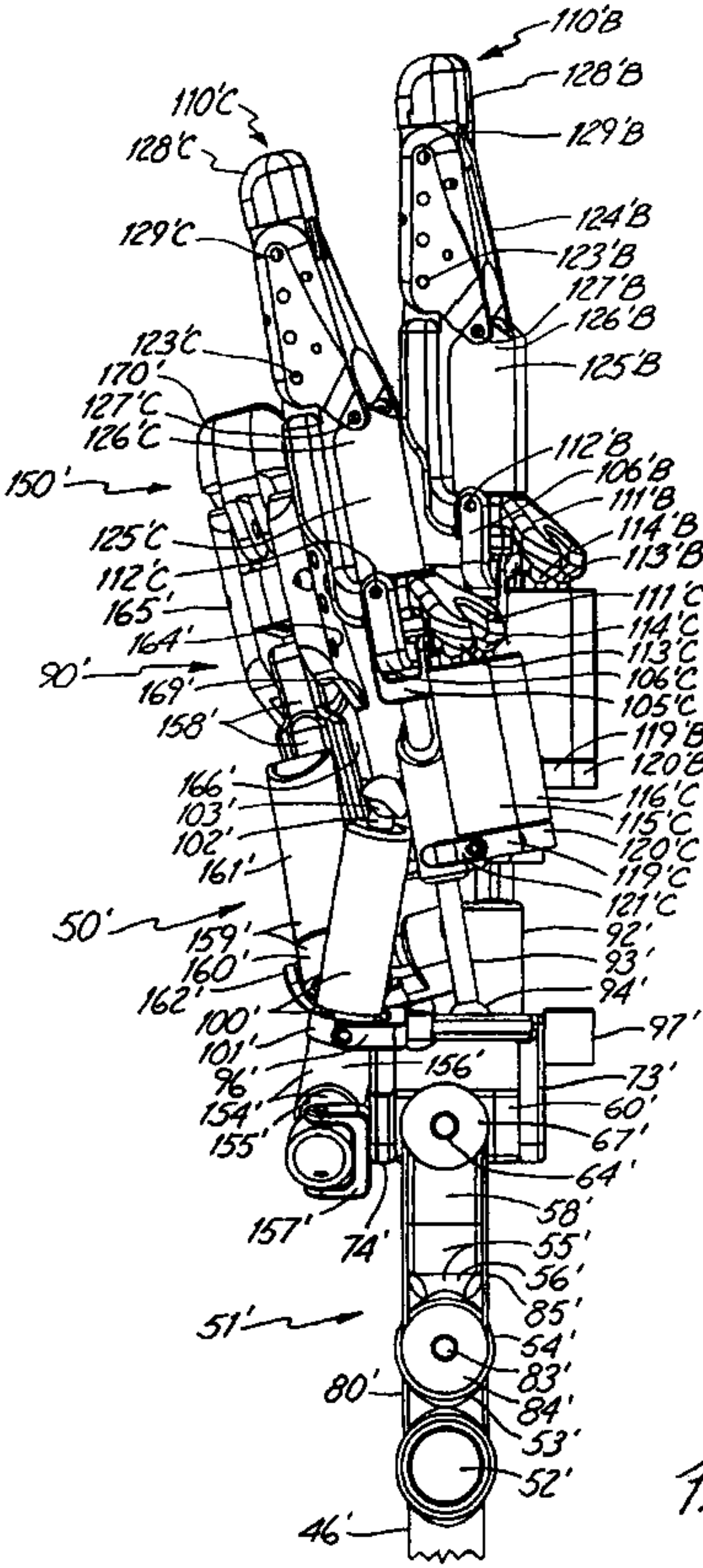
124'B
123'B
110'A
128'A
129'A
124'A
123'A
127'A
126'A
125'B
125'A
111'A
112'A
106'A
111'A
90'
114'A
99'
115'A
98'
116'A
122'A
128'C
129'C
110'C
124'C
123'C
111'B
125'C
150'
111'C
112'C
171'
165'
164'
106'C
170'
105'C
169'
159'
168'
166'
167'
91'
92'
151'
50'
158'
95'
152'
92'
93'
100'
101'
97'
96'
156'
155'
154'
153'
156'
62'
63'
57'
60'
69'
68'
157'
58'
85'
51'
55'
54'
80'
56'
84'
79'
78'
53'
77'
76'
46'
52'

Fig. 11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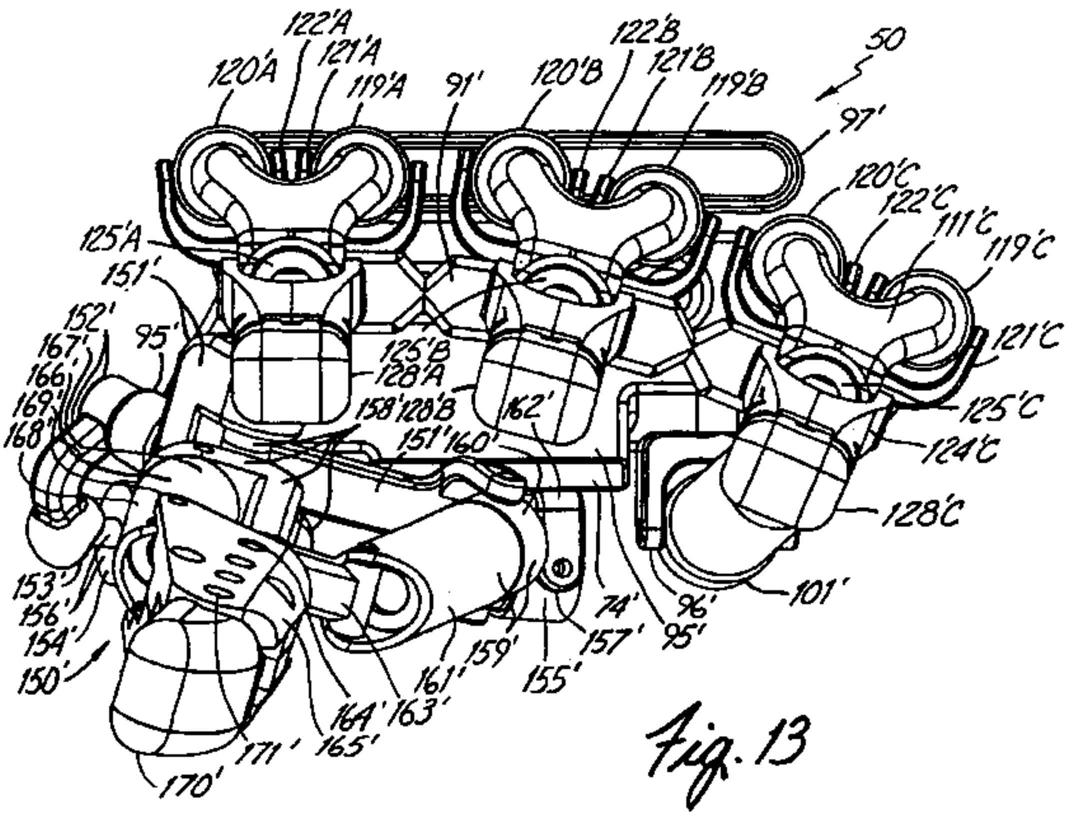
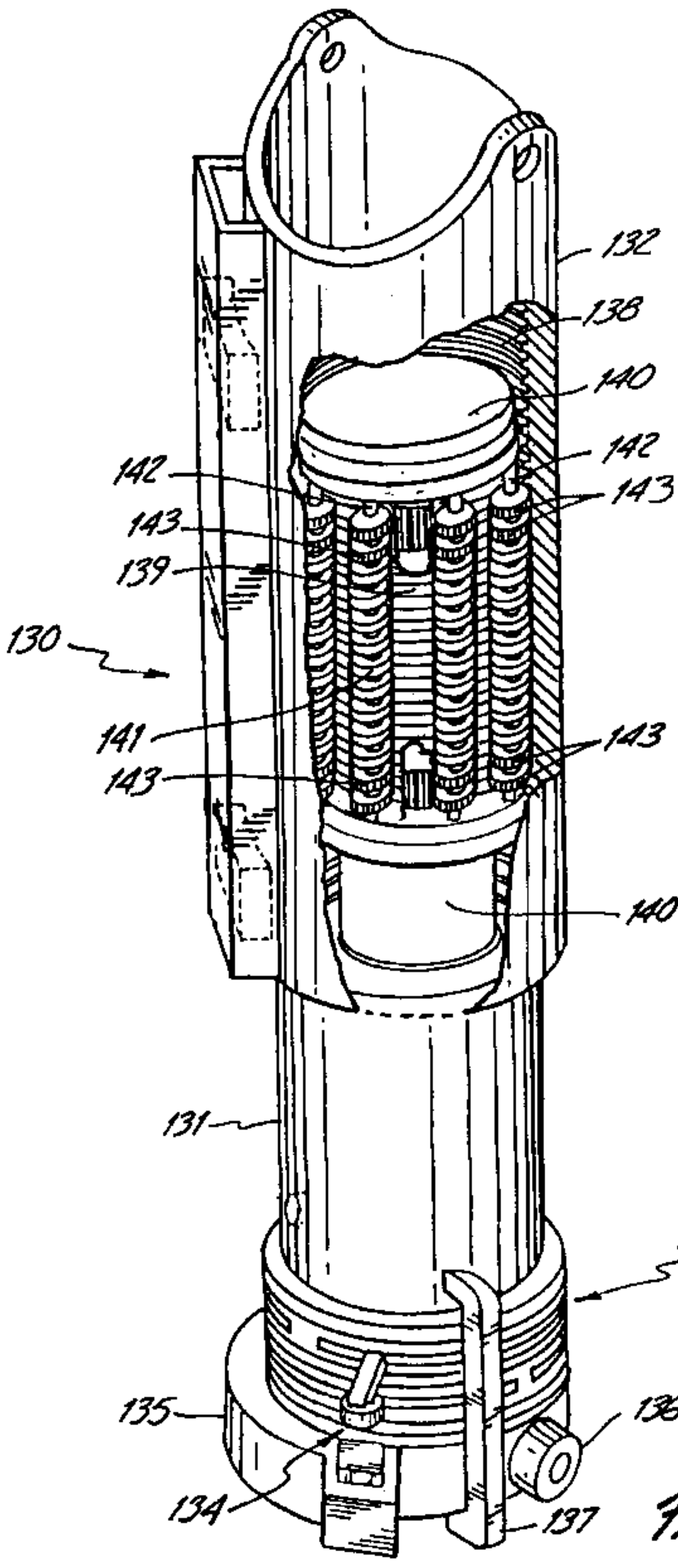
129'B
124'B
123'B
127'B
126'B
125'B
110'C
128'C
129'C
123'C
170'
127'C
126'C
150'
125'C
112'C
165'
164'
90'
169'
158'
166'
103'
102'
161'
50'
159'
160'
162'
100'
101'
96'
154'
155'
157'
74'
51'
80'
46'
112'B
106'B
111'B
114'B
113'B
111'C
114'C
113'C
106'C
105'C
119'B
120'B
116'C
115'C
120'C
119'C
121'C
92'
93'
94'
97'
156'
73'
60'
67'
64'
58'
55'
56'
85'
54'
83'
84'
53'
52'

Fig. 12



122'A
121'A
120'A
119'A
91'
120'B
122'B
121'B
119'B
50
97'
120'C
122'C
111'C
119'C
125'A
151'
152'
167'
166'
169'
168'
95'
125'B
128'A
158'
128'B
162'
151'
160'
121'C
125'C
124'C
128'C
101'
96'
95'
74'
157'
155'
159'
161'
163'
164'
165'
171'
170'
153'
156'
154'
150'

Fig. 13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143
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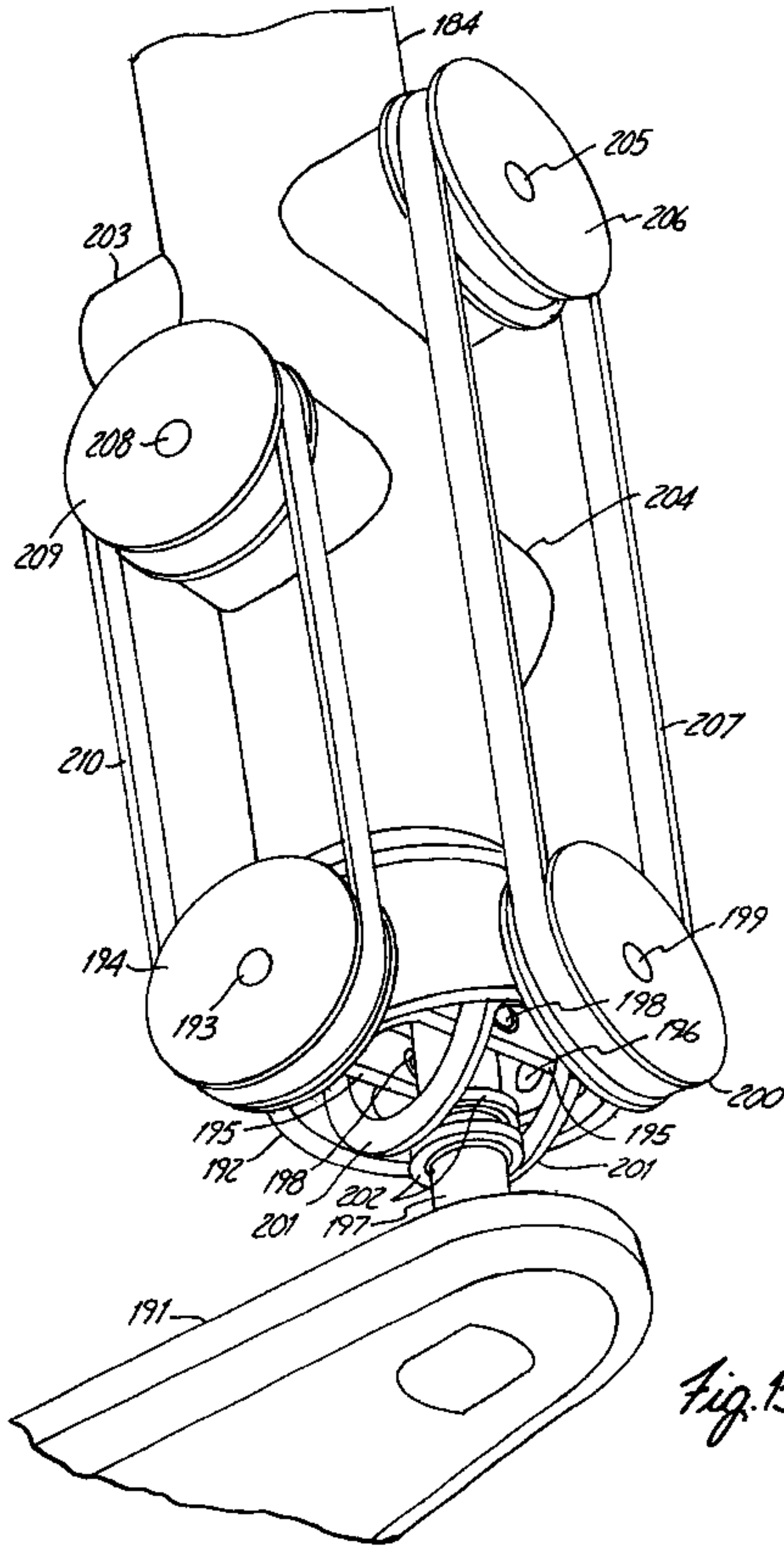
133
135
136
134
137

Fig. 14



184
205
206
203
208
204
209
207
210
199
194
198
193
196
200
195
195
192
201
198
202
201
197
191

Fig.15

ROBOTIC MANIPULATOR

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of Provisional Application No. 60/336,477 filed Oct. 31, 2001 for "Robotic Manipulator".

BACKGROUND OF THE INVENTION

The present invention relates to controlled motion mechanical members used as a mechanical manipulator and, more particularly, to a motion controllable, anthropomorphic mechanical manipulator providing some of the capabilities of an upper human torso.

A need for increased automation in the workplace, especially in those workplace environments unsuitable for humans, and a desire to increase the use of animated figures depicting humans or other characters of ten in entertainment situations, has led to substantial efforts in the development of robotics. As a result, substantial advances have occurred in many aspects of robotics.

An important aspect in robotics is the controlling of mechanical manipulators, the portion of a robot used to change the position or orientation of selected objects. In may instances, such manipulators are desired to have motion capabilities similar to those of a human chest, shoulder, arm, wrist and hand, or portions thereof.

Providing a mechanical manipulator simulating such portions of the human torso presents a difficult design problem. The chest portions of a human supporting a shoulder can be considered to have two degrees-of-freedom in motion possibilities available to it, and the shoulder supporting the arm can be considered to have three degrees-of-freedom in motion possibilities available to it. In addition, the elbow can be considered to have a single degree-of-freedom in its possible motion and the wrist can be considered to have three degrees-of-freedom in motion possibilities available for it. Finally, the human palm can be considered to have a degree-of-freedom in its relative motion possibilities while the fingers and thumb thereon can be considered to have four degrees-of-freedom in the motion possibilities thereof.

A number of mechanical joints or mechanical manipulators have been proposed which attempt to exhibit the motion possibilities of the corresponding human joints, and some of these proposals have actually achieved corresponding capabilities to a significant degree. These joints typically have a base on which one side of the joint is fastened, and from which a force imparting arrangement is provided to operate movable members in this fastened portion of the joint. Mechanical transmission arrangements then couple this motion on this fastened side of the joint to the controlled side of the joint to cause that portion to correspondingly move.

However, such joints have of ten been constructed using a substantial number of parts causing significant expense, and with the result that they are of ten difficult to assemble. Further, such joints of ten fail to have the controlled portion thereof exhibit the desired dexterity and range of motion. In addition, the construction have of ten exhibited bulky geometries which do not appear much like those of the human counterparts. Also, control of the controlled side of the joint has of ten been insufficient in the operator not having convenient controlling arrangements available. FIG. **1** shows a joint, mechanical manipulator, or controlled member motion system, **10**, which can have a very large output operating range in various configurations over which it is free of singularities, and which is operated by various force imparting devices directly or through various drive trains. A compact, ruggedized version of manipulator **10** is shown in FIG. **1** using yoke and shackle arrangements to rotatably secure the pivoting links provided therein.

Thus, FIG. **1** shows a perspective view of manipulator **10** in which manipulator **10** is positioned on a mounting arrangement, **11**, which can be connected with an electric motor arrangement, unseen in these figures, that can rotate mounting arrangement **11** in either the clockwise or counterclockwise direction as selected by the user to thereby carry the remainder of joint or manipulator **10** correspondingly with it in these directions. Directly supported on mounting arrangement **11** is a base support, **12**, shown as a rounded corner rectangular solid structure, though different geometrical shapes can be used, having four arms extending out from the main body of the support at the four thickness surfaces thereof initially parallel to the large surfaces of that support, and then bending at right angles away from mounting arrangement **11**. These extending arms each thereby form something of a "U" shape to provide a capture space between the main support body of base support **12** and itself to result effectively in a yoke to rotatably accommodate the ends of pivoting links (described below) therein which are secured there by the use of a pin extending through the arm and pivot link end into the main body that allows the pivot link to rotate thereabout. A corresponding shroud plate extends from the main body of support **12** to each of these arms on the side of its capture space opposite the side thereof through which pivoting link secured therein extends to add support to that arm.

Support **12** has an opening, **13**, (unseen in FIG. 1) extending along the central axis of rectangular symmetry for support **12** extending out from mounting arrangement **11** to parallel the outer sides of support **12**. Opening **13** extends through support **12** and from there through mounting arrangement **11** along the axis about which it is capable of rotating manipulator **10** so as to be capable of permitting some desired means extend therethrough such as electrical wiring, optical fibers or some mechanical arrangement, or some combination thereof.

Also shown supported directly on mounting arrangement **11** are a pair of linear actuator support pedestals, **14**, (unseen in FIG. 1) connected to mounting arrangement 11 each of which is shown supporting a linear actuator along with the direct mechanical interconnection between that linear actuator and the remaining portions of manipulator **10**. That is, a pair of linear actuators, **15** and **16**, are each rotatably mounted in the corresponding one of pedestals **14** by an outer body thereof, **17**. Linear actuator **16** has an actuator output shaft, **18**, extending from outer body **17** thereof which is directly affixed to a clevis, **19**. Clevis **19** on output shaft **18** of linear actuator **16** is directly and rotatably affixed to a pivoting link, **20**, by a further pin, **21**, through an opening in a boss, **22**, extending from pivoting link **20** (which pin may be in bearings or a bushing mounted in boss **22** positioned about the opening therein). Linear motion by output shaft **18** in actuator **16** outward or inward causes clevis **19** to correspondingly move away from or toward body 17 of linear actuator **16**.

Such motions by clevis **19** forces pivoting link **20** to in turn rotate one way or the other about a pin, **23**, around a rotation axis extending through pin **23** that is more or less perpendicular to the length of link **20**. Pin **23** is directly affixed in an opening in the central rectangular portion of base support **12** and in an opening in an extending arm of base support **12** as two sides of a yoke to extend through the

capture space therebetween and through an opening in the end of pivoting link 20 (which pin may be in bearings or a bushing mounted in the opening in link 20, and pin 23 could be a pivot screw (shoulder bolt) rather than a pin. Such a pivot screw is threaded at the end thereof opposite the screw head only a relatively short distance in from that end to permit its being screwed firmly into base support 12 but only a fixed distance therein to assure a selected length of the screw is exposed outside support 12 The surface of this exposed portion of the screw from support 12 to the screw head is smooth especially if no bearing or bushing is used between this screw and pivoting link 20 lubrication at the least would be likely to be used in this situation).

An identical linear actuator translation drive system for forcing rotational motion of another pivoting link is provided in connection with linear actuator 15. As seen in FIG. 1, a clevis, 19', is affixed to output shaft 18 of linear actuator 15 with the other end of clevis 19' being affixed by a pin, 21', to a further pivoting link, 20', rotatably connected to base support 12, through an opening in a boss, 22', extending from pivoting link 20'. Thus, again, linear motion by output shaft 18 in actuator 15 outward or inward causes clevis 19' to correspondingly move away from or toward body 17 of linear actuator 15 which forces pivoting link 20' to correspondingly rotate in either a clockwise or counterclockwise direction. Pivoting link 20' can rotate on bearings about a pin or screw, 23', not seen in these figures, positioned in an opening therein at its end with pin or screw 23' affixed to the sides of the corresponding yoke in base support 12, and pivoting link 20' again rotates around an axis extending therethrough more or less perpendicular to the length of link 20'.

Pivoting links 20 and 20' are two pivoting links in a plurality of lower pivoting links in manipulator 10, this lower plurality further including two other pivoting links, 20" and 20'" (not all seen in FIG. 1), with extending bosses, 22" and 22'" (not all seen in FIG. 1). Bosses 22" and 22'" are unused in the present situation in which just two linear actuators are used to operate manipulator 10, but can be used with the use of further linear actuators. These last two pivoting links are each capable of rotating on bearings about a corresponding one of pins or pivot screws, 23" and 23'" (not all seen in FIG. 1), respectively, with the corresponding axis of rotation extending therethrough substantially perpendicular to the length of links 20" and 20'". Pins or pivot screws 23" and 23'" are again directly affixed in a corresponding opening in the central rectangular portion of base support 12 and in a corresponding opening in a corresponding extending arm of base support 12 in the capture space therebetween (which pin may be in bearings or a bushing mounted in each of these base support 12 openings so as to be positioned about that opening, and pin 23 could be a pivot screw rather than a pin). Each of pins or pivot screws 23, 23', 23" and 23'" is affixed to base support 12 such that the corresponding one of the plurality of lower pivoting links rotatably coupled to base support 12 thereby rotates about an axis therethrough that intersects, and is perpendicular to the axis of rectangular symmetry of support 12 extending out from mounting arrangement 11, with these rotation axes being separated from adjacent ones by equal angles measured about the symmetry axis, here 90°.

The lower plurality of pivoting links 20, 20', 20" and 20'", in addition to each having an end thereof being rotatably connected to base support 12 by the yokes effectively provided by the central rectangular portion and the corresponding extending arm of that base support as described above, also each have the opposite end thereof formed as

devises with two spaced apart arms that are rotatably connected by four further pins or pivot screws, 24, 24', 24" and 24'", to corresponding pivot holder shackle members, 25, 25', 25" and 25'". Each of these pivoting link devises has a shroud plate extending between the arms thereof on the side opposite that through which a corresponding shackle extends to add support to these two arms. Each of these pivot holder shackle members is formed as a bent link with an opening therethrough at each end to accept a pin extending through it (which pin may be in bearings or a bushing mounted in the link opening positioned about that opening therein), the bend in the link occurring along the width thereof between the two openings each provided near a corresponding end thereof. Each of these pivot holder shackle members 25, 25', 25" and 25'" has an end thereof captured in a shrouded clevis at the end of a corresponding one of the lower plurality of pivoting links 20, 20', 20" and 20'" by a corresponding one of pins 24, 24', 24" and 24'" extending through the opening in that bent link end into the arms of the pivoting link clevis on either side thereof.

The axis of rotation of each of the lower plurality of pivoting links 20, 20', 20" and 20'" through a corresponding one of pins or pivot screws 24, 24', 24" and 24'" in being rotatably coupled to a corresponding one of pivot holder shackle members 25, 25', 25" and 25'", and the axis of rotation of each of these links through a corresponding one of pins or pivot screws 23, 23', 23" and 23'" in being rotatably coupled to base support 12 are, in each link instance, perpendicular to planes therethrough that for each link intersect one another at substantially right angles. These rotation axes for each of these pivoting links are also oriented in directions differing from those in an adjacent pivoting link, i.e. the next pivoting link thereafter around base support 12. This allows pivot holder shackle members 25, 25', 25" and 25'" to be moved by the corresponding pivoting links substantially with respect to base support 12, but for the same length links these pivot holder shackle members will always be in a plane common thereto, and will move about a circle in such planes. Although pivot holder shackle members 25, 25', 25" and 25'" are shown in these figures as extended bent links, this shape is not required but instead other geometrical shapes could be used.

Manipulator 10 is shown in these figures having a further upper plurality of pivoting links. Each of this plurality has an end thereof formed as a clevis formed by two spaced apart arms that is rotatably coupled to each of pivot holder shackle members 25, 25', 25" and 25'" by a corresponding one of a further set of pins or pivot screws, 27, 27', 27" and 27'" (not all seen in FIG. 1) extending through the other end opening of such pivot holder shackle member not connected to a lower pivoting link to be affixed to the two arms of the clevis (which pin may be in bearings or a bushing mounted in the link opening positioned about that opening therein). Again, each of these pivoting link devises has a shroud plate extending between the arms thereof on the side opposite that through which a corresponding shackle extends to add support to these two arms by forming a shrouded clevis.

The axis of rotation of the corresponding one of this upper plurality of pivoting links, in being able to rotate about its pin or pivot screws 27, 27', 27" and 27'", is directed so as to be more or less parallel to the length of the link. There is a corresponding one of a set of angles, 28, 28', 28" and 28'", (not all seen in FIG. 1) of a selected angular magnitude between the axis of rotation of the pivoting link from the lower plurality thereof rotatably connected to each pivot holder member and the axis of rotation of the one of the upper plurality of pivoting links also rotatably connected

thereto as shown in these figures set by the bend in the bent links forming the pivot holder shackle members. The selection of the magnitude of each of angles **28, 28', 28"** and **28'"** effects the capabilities of manipulator **10** as will be described below.

Another set of pins or pivot screws, **29, 29', 29"** and **29'"**, (not all seen in FIG. 1) are each used at the opposite end of a corresponding one of such an upper plurality of pivoting links, **30, 30', 30"** and **30'"** (not all seen in FIG. 1). If manipulator **10** is constructed symmetrically above and below a plane including each of pivot holder shackle members **25, 25', 25"** and **25'"**, i.e., angles **28, 28', 28"** and **28'"** in these figures being bisected by such a common plane, the upper plurality of pivoting links **30, 30', 30"** and **30'"** can be identical in construction with each other and with each of the lower plurality of pivoting links **20, 20', 20"** and **20'"**. Although this is a significant economic factor in manufacturing significant numbers of joint or manipulator **10**, this symmetry is not required for successful operation of such manipulators. However, the nature of the positioning of the output structure in such manipulators for a given rotation of the rotor shafts of motors **15** or **16** will change with differences in the portions of angles **28, 28', 28"** and **28'"** above and below the horizon. Also, the lengths of pivoting links in the upper and lower pluralities thereof need not all be the same to have successful operation of manipulator **10** but, again, the pattern of the positioning of this output structure will change depending on such differences.

The output structure which is controlled in manipulator **10** by motion of linear actuators **15** and **16** has a hole, **31**, provided therethrough to form a rounded corner rectangular solid, open center structure, though different geometrical shapes can be used, resulting in a manipulable support, **32**. Manipulable support **32** has four arms extending out from the main body of the support at the four thickness surfaces thereof initially parallel to the large surfaces of that support, which then bend away at right angles generally toward mounting arrangement **11**. These extending arms each thereby form something of a "U" shape to provide a capture space between the main support body of manipulable support **32** and itself to result effectively in a yoke to rotatably accommodate the ends of the upper pivoting links therein which are secured there by the use of the corresponding one of pins **29, 29', 29"** and **29'"** extending through the arm and pivot link end into the main body that allows the pivot link to rotate thereabout. A corresponding shroud plate extends from the main body of support **32** to each of these arms on the side of the arm capture space opposite the side thereof through which the corresponding pivoting link secured therein extends to add support to that arm.

Again, various items can be extended through opening **31** such as electrical wiring or optical fibers or, in this output situation, a further mechanical device supported on support **32**, or some combination of such features or other alternatives. Also, the output structure as represented by manipulable support **32** can be controlled in manipulator **10** by motion of a complementary set of linear actuators, **35** and **37**, (not seen in FIG. **1** but referenced here to clarify certain subsequent figures) having their bases mounted in actuator support pedestals **14** and their output shafts connected to the two remaining lower pivoting links **20"** and **20'"** either instead of using actuators **16** and **15** connected to lower pivoting links **20** and **20'** as described above, or alternatively also using actuators **15** and **16** to provide greater force and stability.

Each of pivoting links **30, 30', 30"** and **30'"** in the upper plurality thereof is rotatably coupled by a corresponding one of pins or pivot screws **29, 29', 29"** and **29'"** to manipulable support **32**. Here too, each of the plurality of upper pivoting links can rotate on bearings about a corresponding one of pins or pivot screws **29, 29', 29"** and **29'"** positioned in an opening therein at its end with the corresponding one of pins **29, 29', 29"** and **29'"** affixed to the sides of the corresponding yoke in manipulable support **32**, and each of pivoting links **30, 30', 30"** and **30'"** again rotates around an axis extending therethrough more or less perpendicular to the length thereof. These rotation axes are separated from adjacent ones by equal angles measured about the symmetry axis, here again 90° because of the presence of four pivot links. Although the rotation axes of the pivoting links at the rotary couplings thereof to supports **12** and **32** are described as making equal angles with adjacent ones thereof as they occur about those supports, these angles need not be identical about either support, nor identical about one support with those about the other, to be able to position support **32** over a substantial angular range, though providing substantially such identities is of ten convenient.

Pivoting links **30, 30', 30"** and **30'"** in the upper plurality thereof may be connected to the side of manipulable support **32** that is opposite to the side of base support **12** to which the corresponding one of pivoting links **20, 20', 20"** and **20'"** in the lower plurality thereof is connected as shown in FIG. **1** or, alternatively, connected to manipulable support **32** on the same side thereof as the side of base support **12** to which the corresponding one of pivoting links **20, 20', 20"** and **20'"** in the lower plurality thereof is connected. The axis of rotation of such a one of pivoting links **30, 30', 30"** and **30'"** in the upper plurality thereof about its pin or pivot screw coupling it to support **32** extends through that pin or screw more or less perpendicular to the direction of the length of that link, and substantially parallel to the axis of rotation about the pin or pivot screw rotatably coupling the corresponding one of pivoting links **20, 20', 20"** and **20'"** in the lower plurality thereof to base support **12**. The correspondence here between upper and lower plurality pivoting links is established by each being coupled to the same one of pivot holder members **25, 25', 25"** and **25'"**. Again here, as for the pivoting links in the lower plurality thereof, the axis of rotation of one of pivoting links **30, 30', 30"** or **30'"** in the upper plurality thereof about its corresponding one of pins or pivot screws **27, 27', 27"** or **27'"** is substantially perpendicular to a plane which intersects at substantially right angles that further plane which is substantially perpendicular to the axis of rotation of that link about its corresponding one of pins **29, 29', 29"** or **29'"**.

The various structural components of joint or manipulator **10** described in connection with FIG. **1** above are typically formed of a metal or metals, or alloys thereof, appropriate for the intended use, i.e. perhaps stainless steel for a medical use, aluminum or titanium where weight is a primary concern, etc. Many or all of these components could be molded polymeric materials instead.

The center of manipulable support **32** can essentially reach every point on a hemispherical surface about manipulator **10** (and in many link constructions, somewhat beyond such a surface) without the occurrence of loss of control singularity points anywhere in this range of motion. During such motion, as indicated above, pivot holder shackle members **25, 25', 25"** and **25'"** will always intersect a common plane though a different plane at each location of manipulable support **32**. Thus, there is a desire to use manipulator **10** with these capabilities, and to use other robotic structure improvements, to simulate portions of the human body.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a controlled relative motion system having first and second support structures,

the first support structure having a first support offset structure extending along a first axis and the second support structure having a second support offset structure extending along a second axis, connected with an intermediate joint having a base member and a controlled position member that has an output carrier which can be angularly positioned with respect to the base member anywhere over a selected spatial surface. This intermediate joint base is affixed to an interior end of a selected one of the first and second support offset structures with the output carrier affixed to an interior end of that one remaining. A similar first support joint has a base member supported by and affixed with respect to the first support offset structure at an exterior end thereof opposite its interior end along the first axis. A second support joint, also similar to the intermediate joint, has a base member supported by and affixed with respect to the second support offset structure at an exterior end thereof opposite the interior end thereof along the second axis.

One of the first and second support joints as a base is coupled to a further controlled relative motion system having an extended open interior member rotatably coupled to the base for rotating about a corresponding interior member rotation axis along which a pair of spaced apart interior member sides extend so as to have an extended space therebetween. The extended open interior member is rotatably coupled to the base at an end thereof joining the interior member sides at one end of the extended space by a first shaft coupled thereto, and is further rotatably coupled to the base at an opposite end thereof also joining the interior member sides at an opposite end of the extended space by a second shaft coupled thereto.

Also, an output carrier has a pair of output carrier sides spaced apart by a recess space with these output carrier sides being joined in a joining structure on one side of the recess space. The output carrier is positioned to have the extended open interior member in its recess space so that the output carrier sides extend at least in part substantially parallel to the interior member sides to which they are rotatably coupled to rotate about a corresponding output carrier rotation axis substantially perpendicular to the interior member rotation axis. The output carrier is rotatably coupled to the extended open interior member by a follower shaft affixed to the output carrier and rotatably coupled to the extended open interior member.

An interior member first bevel gear is located in the extended space and affixed to the first shaft, and an output carrier first bevel gear is located in the extended space and affixed to the follower shaft to be engaged with the interior member first bevel gear. A plurality of force imparting means is mounted in the base with each of the first and second shafts being rotatably coupled to a corresponding one of these force imparting means.

This further controlled motion system with the output carrier as a base supports an articulated manipulating system capable of engaging selected objects having a subbase rotatably mounted on the base to have a single subbase rotation axis therethrough. A first linear actuator is coupled at one end thereof to the base and coupled at an opposite end thereof to the subbase to be capable of rotating the subbase about the subbase rotation axis. A first effector base is rotatably connected to the subbase to have a first effector rotation axis, and a second linear actuator is coupled at one end thereof to the subbase and coupled at an opposite end thereof to the first effector base to be capable of rotating the first effector base about the first effector rotation axis.

This further controlled motion system with the output carrier as a base also supports a shackle having a pair of arms spaced apart by a recess space which arms are joined in a joining bar on one side of the recess space, an effector base rotatably mounted at a pivot location thereof to and between the separated arms of the shackle so as to leave a recess space between an end of that effector base rotatably mounted to the shackle and the joining bar thereof, a pedestal affixed to the base relatively near to where the subbase is rotatably mounted on the base and having the joining bar of the shackle rotatably coupled thereto. A gripping extension is rotatably coupled to the effector base at an extension coupling location thereof spaced apart from the pivot location thereof, and an extension linear actuator is positioned adjacent to the effector base and coupled at one end thereof so as to have that end positioned at least in part in the recess space of the shackle with that remaining end of the linear actuator rotatably coupled to that gripping extension. Further, a pair of effector linear actuators is provided with each having an end thereof connected to the base at corresponding base connection locations thereon, and each having that opposite end thereof rotatably connected to an effector base at corresponding effector connection locations thereon. Thus, any substantial differentials in movement of these actuators cause corresponding substantial motions of the effector base towards a corresponding one of the base connection locations and so that substantial common movements of these actuators causes substantial motions of the effector base toward or away from both of the base connection locations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a perspective view of a robotic manipulator used in the present invention,

FIG. **2** shows a perspective view of a robot of the present invention simulating a human body,

FIGS. **3**, **4**, **5** and **6** show perspective views of portions of the structure shown in FIG. **2**,

FIG. **7A** shows a cross section view of a part of the structure shown FIG. **6** and FIG. **7B** shows an alternative structure in a cross section view,

FIGS. **8** and **9** show side views of an alternative for portions of the structure shown in FIG. **5**,

FIG. **10A** shows an alternative perspective view of the structure shown in FIG. **5** and FIGS. **10B** and **10C** show side views of an alternative for portions of the structure shown in FIGS. **5** and **10A**,

FIGS. **11**, **12** and **13** show alternative perspective views of the structure shown in FIGS. **5** and **10A**,

FIG. **14** shows a perspective view of portions of the structure shown in FIGS. **5**, **10A**, **11**, **12** and **13**, and

FIG. **15** shows a perspective view of a portion of the structure shown in FIG. **2**.

DETAILED DESCRIPTION

Manipulator, or joint, **10** of FIG. **1** is a very effective controlled output manipulator for use in simulating the motion possibilities of the two degree of freedom joints and other bending structures of the human body. FIG. **2** shows a robot, **40**, reminiscent of the human body with such joints used therein to simulate human shoulders, middle upper torso and hips, and another such manipulator could be added to simulate the neck though not shown.

A control arrangement for robot **40** is operated under the direction of a computer which typically controls operation of a system controller, not shown. This controller has a transmitter therein to transmit information signals to a receiver in

robot **40**, again not separately shown, but which might be located in a portion of that robot in the position of a human head indicated to some extent by a dashed line rendering. This portion of robot **40** also has a transmitter therein for transmitting information signals to the controller which has a further receiver to receive same therein. Alternatively, or as a supplemental control arrangement, other transmitters or receivers, or both, which can interact with the transmitter or receiver, or both, in robot **40** can be provided in items such as household appliances to facilitate robot **40** interacting with them to reduce the control and sensing apparatus that otherwise needs to be provided in robot **40** to support such interaction. Thus, for instance, a robot used to fetch items from a refrigerator might not need a simulated vision system to accomplish such tasks if the refrigerator itself can provide sufficient guide signals to the robot, or at least not as advanced a system as would be required in the absence of such refrigerator based robot guidance. Wiring arrangements are provided through the joints and joint connectors in robot **40** to distribute signals obtained from the receivers therein to the actuators therein intended to respond to them, and to collect signals from sensors therein to be brought to the transmitters therein.

A "tee" structure, **41**, in the upper portion of robot **40** in FIG. **2**, as shown in more detail in FIG. **3**, has the two arms, **42** and **43**, of the crosspiece each canted rearward from the base joining point to be out of alignment with one another so as to form an angle therebetween of less than 180°. Arm **42** has a manipulator, **10A**, like manipulator **10** of FIG. **1**, useful for simulating a human right shoulder, mounted to the end thereof at a right angle to the long axis of mounting arrangement **11A** of manipulator **10A** near its connection to base support **12A** (unseen in FIG. **2**). Linear actuators **35A** and **37A** (connected to lower pivoting links **20"** A and **20'"** A rather than to lower pivoting links **20A** and **20'** A in the manner of linear actuators **16** and **15** in FIG. **1** being connected to lower pivoting links **20** and **20'** there) are mounted on support pedestals **14A** on mounting arrangement **11A** and connected to the corresponding lower pivoting links which can cause manipulable support **32A** of manipulator **10A** to move to simulate selected right human shoulder motion under direction of the controller.

Manipulable support **32A** is connected to an upper arm bar, **44**, which has at its opposite end a yoke, **45**, in which a forearm bar, **46**, is rotatably connected by a pair of pin-like bosses, **47**, each extending through a yoke arm opening to be affixed in the sides of the upper arm bar yoke thereby forming a single degree of freedom joint, **48**, simulating a human elbow. A linear actuator, **49**, is connected between upper arm bar **44** and forearm bar **46** to operate that joint by causing forearm bar **46** to selectively rotate in yoke **45** about pin-like bosses **47**. A motor and a rotational joint arrangement contained within upper arm bar **44** allows it to be rotated over an angular range with respect to manipulator **10A**. A joint and manipulator structure, **50**, simulating a human wrist and hand is mounted on the end of forearm bar **46**, and a motor and a rotational joint arrangement contained within forearm bar **46** allows joint and manipulator structure **50** to be rotated over an angular range with respect to forearm bar **46**.

Similarly, as shown in FIG. **2** and in more detail in FIGS. **3** and **4**, arm **43** has a manipulator, **10B**, like manipulator **10** of FIG. **1**, useful for simulating a human left shoulder, mounted to the end thereof at a right angle to the long axis of mounting arrangement **11B** of manipulator **10B** near its connection to base support **12B**. Linear actuators **15B** and **16B** are mounted on support pedestals **14B** on mounting arrangement **11B** and connected to the corresponding lower pivoting links which can cause manipulable support **32B** of manipulator **10B** to move to simulate selected left human shoulder motion under direction of the controller.

Manipulable support **32B** is connected to an upper arm bar, **44'**, which has at its opposite end a yoke, **45'**, in which a forearm bar, **46'**, is rotatably connected by a pair of pin-like bosses, **47'**, each extending through a yoke arm opening to be affixed in the sides of the upper arm bar yoke thereby forming a single degree of freedom joint, **48'**, simulating a human elbow. A linear actuator, **49'**, is connected between upper arm bar **44'** and forearm bar **46'** to operate that joint by causing forearm bar **46'** to selectively rotate in yoke **45'** about pin-like bosses **47'**. A motor and a rotational joint arrangement contained within upper arm bar **44'** allows it to be rotated over an angular range with respect to manipulator **10B**. A joint and manipulator structure, **50'**, simulating a human wrist and hand is mounted on the end of forearm bar **46'**, and a motor and a rotational joint arrangement contained within forearm bar **46'** allows joint and manipulator structure **50'** to be rotated over an angular range with respect to forearm bar **46'**.

FIG. **5** shows a perspective view of joint and manipulator structure **50'** for simulating a human wrist and hand mounted on the end of forearm bar **46'**. A two degree of freedom positioning joint, **51'**, for simulating a human wrist has a truncated cylindrical shell shaped motor housing, **52'**, affixed to the end of forearm bar **46'** with its axis of radial symmetry oriented perpendicular to the long axis of forearm bar **46'** (structures in joint and manipulator structure **50** mounted on the end of forearm bar **46** similar to those in joint and manipulator structure **50'** mounted on the end of forearm bar **46'** have the same numerical designations there as they do in joint and manipulator structure **50'** but without the following prime mark). Typically, motor housing **52'** has one end open to receive an electrical motor therein with the other end closed. (Positioning joint **51'** can be made a three degree of freedom joint by providing a motor on, and a rotatable connection in, forearm bar **46'** to thereby permit rotating joint and manipulator structure **50'** including positioning joint **51'** about the long axis of forearm bar **46'**).

An intermediate stem portion, **53'**, is affixed at one end thereof to motor housing **52'** to extend therefrom perpendicular to the housing axis of radial symmetry, and also affixed at its other end to another truncated cylindrical shell shaped motor housing, **54'**, having its axis of radial symmetry oriented parallel to that of motor housing **52'**. However, motor housing **54'** has the end thereof open to receive an electrical motor therein being adjacent to the closed end of motor housing **52'** so as to be on the opposite side of intermediate stem portion **53'** from the open end of motor housing **52'** that is open for the same purpose, and typically, again, the other end of motor housing **54'** is closed.

Forearm bar **46'** and intermediate stem portion **53'** typically have openings extending therethrough to allow control wiring to be installed. Motor housing **52'**, in addition to having some of such wiring terminate there for the motor to be provided therein, also has sufficient space therein to allow such wiring to pass from forearm bar **46'** to intermediate stem portion **53'** to reach motor housing **54'** for the motor to be provided there. Additional wiring, or other facilitating means, may also be passed through such openings and spaces if needed.

A clevis, **55'**, is affixed to motor housing **54'** to have its stem portion, **56'**, extend from that motor housing perpendicular to the housing axis of radial symmetry. Stem portion

56', in so extending, subsequently diverges therealong into two spaced apart arms, 57' and 58', as can be better seen in the rear perspective view of FIG. 6. These diverging arm structures first curve away from each other approximately perpendicularly to stem portion 56' and then further extend to again curve at more or less right angles to thereby parallel one another with a space therebetween (i.e. the arms together follow approximately a "U" shape supported on the clevis stem portion). An opening is provided in the ends of each of these arms across the space between the arms from one another so that they share the same axis of radial symmetry parallel to those of housings 52' and 54'.

A rotatable bridge carrier, 60', is positioned between clevis arms 57' and 58', and is shaped approximately in the form of a rectangular solid shell with the bottom side thereof in FIGS. 5 and 6 omitted as better seen in FIG. 6 as a result of the cut away provided in carrier 60' there. As best seen in the section view of FIG. 7A, taken at the position indicated in FIG. 6, carrier 60', across from the opening in the end of clevis arm 57' in which there is positioned a bushing, 61', has the end of a cylindrical shaft, 62', affixed thereto at a short side thereof centered along its width. Shaft 62' extends through bushing 61' to be positioned in the opening in clevis arm 57' to thereby have clevis arm 57' rotatably support carrier 60' at one of the two short sides thereof. Shaft 62' also extends beyond clevis arm 57' to have a pulley, 63', affixed to the remaining end thereof.

The remaining short side of carrier 60', across from the short side thereof from which shaft 62' extends, has an opening therein centered along the width thereof that is across from the opening in the end of clevis arm 58' to have a common axis of radial symmetry. A further cylindrical shaft, 64', extends through a bushing, 65', positioned in the opening of the remaining short side of carrier 60', and through a bushing, 66', of clevis arm 58' to extend past clevis arm 58' to have a further pulley, 67', affixed to the end thereof. The portion of shaft 64' extending into the interior opening in carrier 60' extends to a bevel gear, 68', and has a diameter increase between just inside the short wall of carrier 60' and bevel gear 68' resulting in a larger cylindrical shaft portion in the interior of carrier 60' to thereby serve to retain that shaft within the interior of carrier 60'. Clevis arm 58' thus rotatably supports carrier 60' at the remaining one of the two short sides thereof so that clevis 55' and carrier 60' together form a revolute joint having an axis of rotation that includes the parallel, end-to-end axes of radial symmetry of shafts 62' and 64'.

Bevel gear 68' in the interior opening of carrier 60' meshes with a further bevel gear, 69', positioned around a further cylindrical shaft, 70'. Each of the two long sides of carrier 60' across from one another has an opening therein opposite the other centered along the lengths of those sides such that the common axis of radial symmetry of these two openings intersects, and is perpendicular to, the common axis of radial symmetry of the two openings in the short sides of carrier 60'. These long side openings each has therein a corresponding one of a pair of bushings 71' and 72', through and past which shaft 70' extends to have its ends each affixed to the adjacent wall provided by a corresponding one of spaced apart flange sides, 73' and 74', of an output positioner, 75', so that carrier 60' across its width is positioned between flange sides 73' and 74'. Output positioner 75' is thus rotatably supported by carrier 60' so they together form a further revolute joint having an axis of rotation that is common with the axis of radial symmetry of shaft 70'. Flange sides 73' and 74' of output positioner 75' extend parallel to one another with the space therebetween being

maintained in addition to shaft 70' by an output support plate affixed to the ends of the flange sides opposite those ends thereof near to the corresponding connections of the ends of shaft 70'.

This open chain of two revolute joints forms a spherical linkage or joint because of the intersection of the two axes of rotation of the two revolute joints which substantially simplifies the joint output guidance problem for the controller because of the existence of closed form solutions to the equations expressing the position of positioner 75' as a function of the positions of shafts 62', 64' and 70'. However, the control of the two joints is complicated by their not being completely decoupled since the rotation of the first revolute joint formed by carrier 60' and clevis 55' forces gear 69' along gear 68' if the latter gear is held stationary by motor 81' thereby leading to an angular change of the second revolute joint formed by positioner 75' and carrier 60' unless countered by the controller if just the original rotational motion of the first revolute joint is desired. The range of possible rotation about the first and second revolute joints axes of rotation is, in each instance, less than a full circle because of interference from adjacent structures.

An alternative positioning joint, 51''', using a differential gear arrangement is shown in FIG. 7B which, if operated on a differential basis, allows full decoupling. An extended version of shaft 62' of FIG. 7A, designated 62''', rotatably extends through clevis arm 57' and bushing 61' and also rotatably extends through the corresponding short side of rotatable bridge carrier 60' and a further bushing, 61''', to support on its end within the carrier a further bevel gear, 68''', across from bevel gear 68'. Also, shaft 70' is replaced by two shorter shafts, 70''' and 70'''', with shaft 70'''' now supporting on its end within bridge carrier 60' bevel gear 69' engaged with bevel gears 68' and 68'''. Shaft 70'''' is an idler shaft rotatably coupled to flange side 73' through a further bushing, 71'''. Shaft 70''' supports on its end within carrier 60' a further bevel gear, 69''', across from bevel gear 69' and also engaged with bevel gears 68' and 68'''. Rotating shafts 64' and 62''' in a common direction at a common speed rotates bridge carrier 60' and output positioner 75' together without rotating positioner 75' with respect to carrier 60', and allows greater torque to be supplied because or rotating both shafts together. Differentials in the rotation of these two shafts results in rotating positioner 75' with respect to carrier 60', but again possibly with greater torque such as if both shafts are rotated in opposite directions.

Returning to the configuration of FIG. 7A, rotation of carrier 60' about the first revolute joint axis of rotation is driven by an electrical motor, 76', (not seen in FIGS. 5, 6 and 7 though seen in a further figure introduced below) provided in motor housing 52'. Motor 76' has an output shaft connected to a speed reduction gearbox, 77', having an output shaft, 78', (not seen in FIGS. 5, 6 and 7 though seen in a further figure introduced below) affixed to a drive pulley, 79'. A drive belt, 80', couples drive pulley 79' to driven pulley 63' to enable motor 76' to rotate pulley 63' and shaft 62', and so carrier 60', over a selected angular range in the associated possible range of rotation under direction of the control system connected to motor 76' by wires provided as described above.

Similarly, rotation of positioner 75' about the second revolute joint axis of rotation is driven by an electrical motor, 81', provided in motor housing 54'. Motor 81' has an output shaft connected to a speed reduction gearbox, 82', having an output shaft, 83', affixed to a drive pulley, 84'. A drive belt, 85', couples drive pulley 84' to driven pulley 67' to enable motor 81' to rotate pulley 67' and shaft 64', and so

positioner 75' through gears 68' and 69', over a selected angular range in the associated possible range of rotation under direction of the control system connected to motor 81' by wires provided as described above. Having the motors 76' and 81' positioned with their motor output shafts parallel to one another results in a structural configuration for positioning joint 51' that is relatively wide compared to its thickness to thereby simulate the relative dimensions of a human wrist.

Changing the ratio of diameters of drive pulleys 79' and 84' to the diameters of the their corresponding driven pulleys 63' and 67' does not significantly affect this configuration result but does allow trading torque and precise positioning for speed of angular change in the drive pulleys, or vice verse. A similar result occurs for changing the ratio of teeth in gears 68' and 69'.

Positioner 75' supports on the output support plate thereof, and thus selectively positions, an end manipulator, 90', for simulating a human hand and, to do so, has five further structures mounted thereon as part of end manipulator 90' with a small portion of each being seen in FIG. 6. A complete perspective view of end manipulator 90' taken from the side of positioner 75' having flange side 74' thereon is seen in FIG. 5.

Shown there is a human palm-like structure, 91', supported on two pedestals including a fixed pedestal, 92', that is fixedly attached to positioner 75' toward one end thereof by a base that is asymmetrical in being longer in the long direction of the support plate of positioner 75' parallel to flange sides 73' and 74' than it is wide where joined with the support plate of positioner 75', this base rising to a cantilevered support plate extending over the support plate of positioner 75' in its longer direction and extending parallel thereto. The other pedestal supporting palm-like structure 91' is a moveable pedestal, 93', in the form of a truncated cylinder where rotatably connected to the support plate of positioner 75' by the ball in a ball and socket joint, 94', with this support plate providing the socket at a location between the attachment of the base of pedestal 92' to the support plate of positioner 75' and the nearest end of that plate.

On the opposite end of the support plate of positioner 75' is provided a support ring, 95', mounted so that a plane including the perimeter of the ring is canted from a plane including the support plate of positioner 75' toward a direction opposite the direction flange sides 73' and 74' extend therefrom. A clevis, 96', generally shaped like clevis 55' described above is rotatably attached by its base to the support plate of positioner 75' adjacent to flange side 74' across from pedestal 92' and 93'. Finally, a wiring harness holder, 97', is attached to positioner 75' across flange side 73' to hold wiring for linear actuators used in the remainder of end manipulator 90'.

The cantilevered support plate of fixed pedestal 92' has rigidly affixed thereto two subpedestals, 98' and 99', each shaped as a truncated cylinder at its attachment point and along a portion of its extent. Subpedestals 98' and 99', and moveable pedestal 93', each extend through an opening in, and pass beyond, palm-like structure 91'. Palm-like structure 91' is formed of a flexible, polymeric material, and has thin linear regions in this polymeric material extending approximately parallel to the subpedestals that serve to segment it into three sections which can bend with respect to adjacent ones thereof along these linear regions. That is, these sections can bend back and forth relative to adjacent ones thereof about axes in a direction more or less parallel to the direction of extent of moveable pedestal 93' and of subpedestals 98 and 99'.

The opening in the section of palm-like structure 91' through which subpedestal 99' extend is located at the end of the cantilevered support plate of fixed pedestal 92' farthest from the base thereof, and is thus one of the outer sections of palm-like structure 91'. The opening in the other outer section of palm-like structure 91' through which moveable pedestal 93' extends is located at the opposite end of palm-like structure 91'. This leaves the remaining opening in palm-like structure 91' through which subpedestal 98' extends centered in the middle section between the two outer sections. The outer segment of palm-like structure 91' through which subpedestal 99' extends and a portion of the middle segment thereof abut the surface of the cantilevered support plate in fixed pedestal 92'.

This arrangement allows moveable pedestal 93', and the outer section of palm-like structure 91' through which it extends, to be moved with respect to the other two sections of palm-like structure 91' about ball and socket joint 94' and about the linear region separating this outer section from the middle section of palm-like structure 91'. The source of such movement is provided by a linear actuator, 100', having its base, 101', (which may contain a force sensor) rotatably connected in the openings in the ends of the arms of clevis 96'. The output shaft and outer body, 102', of linear actuator 100' is connected in a ball and socket joint, 103', in which the ball is provided at the end of output shaft 102' and the socket is provided attached to moveable pedestal 93' through a portion of the outer section of palm-like structure 91' through which moveable pedestal 93' extends. Thus, the control system indicated above which operates linear actuator 100' through wires (not shown) can cause output shaft 102' of that actuator to extend and retract to thereby cause moveable pedestal 93' at the location of the section of palm-like structure 91' through which it extends to move toward either side of the middle section of palm-like structure 91' about ball and socket joint 94' to provide akin to the squeezing together and moving apart of human palm portions.

At the ends of subpedestals 98' and 99' opposite the ends thereof affixed to the cantilevered support plate of fixed pedestal 92', and at the end of moveable pedestal 93' opposite the end with ball and socket joint 94', the cylindrical shaped portions of each serve as a clevis base and there beyond diverge into a pair of parallel arms with openings therein like clevis 55' above to form a corresponding one of three clevises, 105' A, 105' B, and 105' C Each of three shackles, 106' A, 106' B, and 106' C in the form of a base with two spaced apart parallel arms extending perpendicularly thereto with end openings to thereby resemble a U-shape, have that base thereof rotatably mounted between the arms of a corresponding one of devises 105' A, 105' B, and 105' C The long extent direction of a shackle base is perpendicular to the axis of rotation thereof extending through the openings in the arms of the corresponding clevis, an axis that is approximately perpendicular to the long extent direction of the support plate of positioner 75'. Each of these clevis and shackle pairs together form an open chain of two revolute joints (including the rotatable connection to the shackle arms in the openings therein to be described below) that serve as a universal joint.

Alternatively, as shown in FIGS. 8 and 9, such a joint can be provided by having moveable pedestal 93', or subpedestals 98' and 99', or all of them, merge into a truncated, curved axis rectangular solid shell, 107', to thereby have a curved, rectangular cross-section slot therethrough. A rectangular cross-section slide, 108', having a axis symmetry following a semicircle is then inserted in this slot. Slide 108' has

openings at each end thereof through which truncated cylindrical pins **109'**, can be inserted and attached to the structure that is to rotate on these pins.

The structures that are to rotate on pins **109'**, or in shackles **106'** A, **106'** B, and **106'** C are shown in FIG. **5** rotatably attached to those shackles, and are a corresponding one of three more or less aligned effectors, **110'** A, **110'** B, **110'** C, each of which forms a more or less planar linkage. However, because each of effectors **110'** A, **110'** B, **110'** C can rotate about an axis extending between the arms of a corresponding one of shackles **106'** A, **106'** B, and **106'** C and because shackles **106'** A, **106'** B, and **106'** C can rotate about an axis extending between the arms of the corresponding one of devises **105'** A, **105'** B, and **105'** C that is perpendicular to the corresponding axis of rotation of its effector rotatably held therein, effectors **110'** A, **110'** B and effectors **110'** A, **110'** B, **110'** C **110'** C, though planar linkages themselves, can also rotate side to side out of the linkage plane.

Each of these effectors has a corresponding one of three effector bases, **111'** A, **111'** B, **111'** C Each of these effector bases has a plateau well pivot region which is rotatably connected by a corresponding one of three pin sets, **112'** A, **112'** B, **112'** C, to the opening in the arms of a corresponding one of shackles **106'** A, **106'** B, and **106'** C, i.e., on the other side of the corresponding one of the universal joints formed at the ends of moveable pedestal **93'** and subpedestals **98'** and **99'**. Thus, the axis of rotation of each of these effectors extending through these pins is perpendicular to the primary direction of extent of the plateau in its plateau well pivot region direction. Extending more or less perpendicularly from one side of the plateau well pivot region of each of the base effectors along its direction of primary extent, and so perpendicularly to the axis of rotation through the corresponding one of these pin sets, is an extension support structure that nearby is curved in a right angle to be perpendicular to the direction of primary extent of that plateau well pivot region. Also extending from the plateau well pivot region on the other side thereof at an incline with respect to the direction of primary extent of that plateau well pivot region is an inclined dual wing drive structure. Some aspects of these can be better seen in FIG. **10A** which provides a perspective view of the other side of joint and manipulator structure **50'** from that shown in FIG. **5**, in FIG. **11** which provides a perspective view of the same side of joint and manipulator structure **50'** shown in FIG. **5** but from a different perspective, in FIG. **12** which provides a perspective view of the side of joint and manipulator structure **50'**, and in FIG. **13** which provides a perspective view of the top of joint and manipulator structure **50'**.

Each of the two wings of the inclined dual wing drive structure of effector base **111'** A is connected by a corresponding one of a pair of ball and socket joints, **113'** A and **114'** A, to one of a pair of linear actuators, **115'** A and **116'** A, at the corresponding one of the outer body and output shafts thereof, **117'** A and **118'** A. The sockets of ball and socket joints **113'** A and **114'** A are provided in a corresponding one of two wings in the inclined dual wing drive structure of effector base **111'** A, and the balls are provided affixed to output shafts **117'** A and **118'** A. The bases, **119'** A and **120'** A, of linear actuators **115'** A and **116'** A, respectively, (each of which may contain a force sensor) are each rotatably connected in the openings in the ends of the arms of a corresponding one of a pair of clevises, **121'** A and **122'** A. Each of clevises **121'** A and **122'** A is shaped like clevis **55'** described above, and each has its stem portion rotatably connected to the cantilevered support plate of fixed pedestal **92'** on the side thereof shown in FIG. **10A**.

In FIG. **10B**, linear actuators, **115'''** A and **116'** A, are shown as alternatives to linear actuators **115'** A and **116'** A in FIG. **10A**. Actuator **116'''** A is shown moved around the edge of pedestal **92'** to be partially in front of actuator **115'''** A to thereby reduce the lateral extent of that actuator pair across pedestal **92'** which aids in allowing another effector, **110'** D, to be mounted on that pedestal. In addition, as shown for the example of actuator **15'''** A in FIG. **10C** that is similar to the other linear actuators shown in FIG. **10B**, actuator 115''' A is held rigidly to prevent any translation rotation of the outer body thereof by the gripping arms of a clip, **115''''** A, that is mounted to pedestal **92'** by a base provided at the joining point of those arms. An actuator output extension, **115'** A, is formed with a threaded rod having a hexagonally faceted sphere-like end that is provided captured in a reduced opening recess in the end of the output member of actuator **115'''** A as a ball and socket joint, and with a cylindrical nut with an interior thread also having a hexagonally faceted sphere-like end to be captured in a wing of the inclined dual wing drive structure of effector base **111'** A to form ball and socket joint **113'** A. Screwing this nut a suitable distance on the threaded rod allows adjusting the length of actuator output extension **115'** A. The following description returns to the arrangement of FIG. **10A**.

Thus, various combinations of extensions and retractions of output shafts **117'** A and **118'** A of the linear actuators **115'** A and **116'** A, respectively, causes the inclined dual wing drive structure of effector base **111'** A to correspondingly rotate about its axis of rotation extending through pin set **112'** A, and the inclined dual wing drive structure of effector base **111'** A plus shackle **106'** A to correspondingly rotate about the axis of rotation of shackle **106'** A extending through the arms of clevis **105'** A. That is, linear actuators **115'** A and **116'** A are capable of forcing effector base **111'** A to any angle with respect to vertical within a limited angular range about the vertical in FIGS. **5**, **10A**, **11**, **12** and **13** substantially followed by the extension support structure of effector base **111'** A in the straight-up position thereof in those figures. Extending or retracting the moveable ends of actuators **115'** A and **116'** A in unison forces effector base **111'** A toward one side or the other of palm-like structure **91'** with the combined forces supplied by each actuator, while differentials in the motions between output shafts **117'** A and **118'** A of these actuators result in side-to-side motions of effector base **111'** A plus shackle **106'** A. As a result, combinations of such motions allow choosing any desired angle for effector base **111'** A with respect to the above described vertical within a limited range. The angular range possible for effector base **111'** A is clearly limited mechanically by interference between that effector and structures on the side of positioner **75'** at which flange side **74'** is provided, by the maximum excursions of output shafts **117'** A and **118'** of actuators **115'** A and **116'** A from the bases thereof, and by the locations of any adjacent effector bases and the location of an opposing effector base not yet described. Practically, however, the angular range limits for effector base **111'** A will be established by operating controls provided in the controller with respect to actuators **115'** A and **116'** A to limit the excursions of output shafts **117'** A and **118'** thereof with respect to the corresponding base for the conditions expected to be encountered by effector base **111'** A during operation thereof.

The extension support structure of effector base **111'** A extending from the other side of the plateau well pivot region thereof has an opening at the far end of that structure through which a pivot pin, **123'** A, is inserted to rotatably connect to effector base **111'** A to a first gripping extension,

124' A. Extension 124' A has a clevis-like end with two extensions between which the end portion of the extension support structure of effector base 111' A is held by pivot pin 123' A extending therethrough and through the two extensions of clevis-like end of the extension.

A linear actuator, 125' A, has a base end thereof (unseen in these figures but which may contain a force sensor) affixed in the hole, or well, provided in the plateau of the plateau well pivot structure of effector base 111' A so that the end of this base extends past pivot pins 112' A as fitted into that well and so into the region between the arms of shackle 106' A. This positioning of the base of linear actuator 125' A down into this well thereby keeps relatively short the distance between the pivot point of effector base 111' A about the axis of rotation established by pins 112' A and the pivot point for first gripping extension 122' A about the rotation axis thereof determined by pins 123' A. The end of the moveable outer body, 126', of actuator 125' A is rotatably connected between a pair of extensions forming a yolk in first gripping extension 124' A by further pair of pivot pins, 127' A. Extensions and retractions of moveable outer body 126' of linear actuator 125' A forces first gripping extension 124' A to rotate about pins 123' A toward one side or the other of effector base 111' A, typically as part of a gripping process with respect some adjacent object in providing a further link in the open linkage chain simulating a human finger to increase the capture arc thereof established by its extent. As shown in FIG. 10B, an alternative linear actuator, 125''' A, can be used in place of linear actuator 125' A held by a clip to effector base 111' A.

A second gripping extension, 128' A, has a portion thereof rotatably connected to first gripping extension 124' A between portions thereof forming a further yoke by a pin, 129' A, fixed in these portions at the end of the first gripping extension opposite the end having a yoke connected to effector base 111' A. Pin 129' A also has a gear centrally mounted thereon. This gear is engaged with gears not seen in first gripping extension 124' A forcing second gripping extension 128' A to rotate with respect to first gripping extension 124' A when the latter is rotated with respect to effector base 111' A again typically to further a gripping process by adding another link in the chain to further increase the capture arc thereof.

The remaining effectors 110' B and 110' C in FIG. 10A are constructed similarly to, and are operated similarly to, effector 110' A. A description of the construction and operation for either of the remaining effectors 110' B and 110' C thus follows from the foregoing such descriptions for effector 110' A by substituting the corresponding one of the letters B or C for the letter A in the designations used in those descriptions of effector 110' A above. Similarly, the remaining effectors 110' B, 110' C and 110' D in FIG. 10B are constructed similarly to, and are operated similarly to, effector 110' A in that figure but with a positioning difference. Instead of having one base effector linear actuator in front of the other to reduce the lateral extent of the pair across the lateral extent of pedestal 92' as for linear actuators 115''' A and 116''' A, the other base effector linear actuator pairs, 115''' B and 116''' B, 115'' C and 116' C, and 115' D and 116''' D, alternate in distance away from the corresponding base effector connection points within a pair and from pair to pair. In doing so, they partially overlap along the directions to the base effectors so that the output ends of some of these linear actuators face in part the opposite ends of other ones of these actuators to thereby reduce the lateral extent of each pair and the lateral extents of the group of pairs thus allowing adding effector 110' D to those mounted on pedestal 92' to give a more complete and proportional simulation of a human hand.

FIG. 14 shows a perspective view of a linear actuator, 130, of the kind used in both joint and manipulator structure 50 and joint and manipulator structure 50' in FIGS. 5, 10A, 11, 12 and 13. Actuator 130 has a base, 131, more or less radially symmetric about a long axis of actuator 130 in the form approximately of a truncated cylindrical shell, and an outer body, 132, partially thereabout also in the form approximately of a truncated cylindrical shell more or less radially symmetric about the actuator long axis but of a larger interior diameter than the outer diameter of base 131. (Alternatively, outer body can additionally have an output shaft centered about the actuator long axis thereon, and affixed to, the end thereof rather than the openings across from one another at the end thereof as shown.) Base 131 has an unseen electric motor provided in its shell, and outer body 132 is driven by this motor to linearly extend or retract under the direction of the unseen control system, connected to the motor by unseen wiring, which determines when current is to be supplied to this motor to cause rotation in one direction or the other of its rotor.

Base 131 has a force sensor, 133, formed of a multiple slitted side truncated cylindrical resulting in partially separated rings that effectively become a spring that can be expanded or compressed by axial forces on actuator 130 that can be measured by measuring the resulting distances of expansion or compression. These distances measurements are made, for instance, using a magnet and a magnetic sensor pair, 134, mounted on force sensor 133 and on an actuator holder, 135, used for rotatably mounting actuator 130 typically in a clevis by a pair of pins, 136, protruding therefrom on opposite sides thereof. A limiter, 137, limits the expansion distance of force sensor 133.

Outer body 132 has spiral threading, 138, on its inner surface, and corresponding spiral threading, 139, is provided on a motor output shaft, 140, connected to the motor in base 131. Engaged with both threadings 138 and 139 are helical threads, 141, located at various radial positions between threadings 138 and 139 provided about a shaft, 142, having in common thereon a pair of gears, 143, mounted and affixed to the same shaft at each end of the helical thread thereon to maintain rotational phase with motor output shaft 140 having meshing gears thereon. The presence of the helical thread shafts between threadings 138 and 139 rather than these threadings being directly engaged with one another results in substantially reduced friction, speed reduction and reduced backlash.

A further effector, 150', and to a varying degree an opposing effector with respect to effectors 110' A, 110' B, 110' C described above, is provided as a human thumb-like effector and is mounted on positioner 75' using support ring 95'. Effector 150' is again a more or less planar linkage but, further, is provided to be specifically rotatable in a bushing provided in the opening in support ring 95'. Thus, a ring supported carrier, 151', has a cylindrical shaft extending through and past the opening of support ring 95' and the bushing therein.

On the side of support ring 95' facing in part the same direction as the side of the support plate of positioner 75' in facing bridge carrier 60', ring supported carrier 151' has, on the portion of the carrier cylindrical shaft extending past support ring 95', a crank arm, 152', affixed thereto with a clamping ring from which a bent shaft extends. The bent shaft at its other end is joined in a ball and socket joint, 153', connecting it with a linear actuator, 154', having a base, 155',

(which may contain a force sensor) and an output shaft, 156'. Base 155' of linear actuator 154' is rotatably connected between the arms of a clevis, 157', like clevis 55' described above, having its base stem rotatably connected to flange side 74' of positioner 75'. A socket for ball and socket joint 153' is provided on the end of crank arm 152', and the ball is affixed to the output shaft 156' of linear actuator 154'. Wiring, not shown, connects linear actuator 154' to the controller for directing the operation thereof.

Carrier 151', considered on the opposite side of support ring 95', has as a part thereof, at the other end of the cylindrical shaft thereof extending through support ring 95', a base plate side of a right angle bracket affixed to that shaft end perpendicularly across the shaft axis of radial symmetry with this base plate side being shaped more or less as a rectangular solid. This right angle bracket has a further perpendicular plate side to form this bracket that extends at a right angle from an edge of the base plate side in a direction opposite to the carrier cylindrical shaft affixed to the base plate side as just described, this perpendicular plate side having an opening therein in which a bushing is positioned. The base plate side of the right angle bracket also has an inclined cantilevered plate extending from another side thereof adjacent to the perpendicular plate side at an angle to thereby be inclined partially in the direction of the perpendicular plate side and so in a direction opposite that from which the carrier of the cylindrical shaft extends from the base plate side but at an angle that is less than a right angle to the base plate side.

A gripping effector base, 158', has therein a cylindrical shaft portion which extends into a stub shaft by being bent to have a right angle with the axis of radial symmetry of the long part of the effector base cylindrical shaft portion. This stub shaft part is inserted in the bushing in the opening in the perpendicular plate side of the right angle bracket of carrier 151' so as to be rotatably connected thereto. The long axis of radial symmetry of the cylindrical shaft portion in the part thereof outside of the stub shaft in gripping effector base 158' intersects the inclined cantilevered plate of carrier 151'.

A linear actuator, 159', for rotating gripping effector base 158' about the axis of radial symmetry of the stub shaft thereof has a base, 160', (which may contain a force sensor) and an output body shell, 161'. Base 160' of linear actuator 159' is rotatably connected between the arms of a clevis, 162', like clevis 55' described above, extending from the far end of the inclined cantilevered plate of carrier 151'. Output body 161' of linear actuator 159' is rotatably connected to a drive beam, 163', affixed at right angles to gripping effector base 158' at a point approximately two-thirds the length of the long part of the cylindrical shaft portion of this effector base from the right angle bend leading to the stub shaft part thereof. Again, wiring, not shown, connects linear actuator 159' to the controller for directing the operation thereof.

Here, too, various combinations of extensions and retractions of output shaft 156' and output body 161' of the linear actuators 154' and 159', respectively, causes carrier 151' to correspondingly rotate, in the first instance, about its axis of rotation extending through its cylindrical shaft passing through support ring 95' to thereby include in that axis the axis of radial symmetry of that shaft, and, in the second instance, causes gripping effector base 158' to correspondingly rotate about its axis of rotation which is the axis of radial symmetry of the stub shaft in gripping effector base 158'. That is, linear actuator 154' is capable of forcing gripping effector base 158' to rotate in support ring 95' to face any one of aligned effectors 110' A, 110' B, 110' C to a selected degree under direction of the controller to thereby

provide a selected gripping position arrangement between them, and linear actuator 159' is then capable under direction of the controller of forcing gripping effector base 158' toward or away from such an aligned effector or effectors, and their respective gripping extensions, so as to close or open the gap therebetween to thereby begin or end a gripping process about some object positioned therebetween.

The angular range possible for gripping effector base 158' is clearly limited mechanically by interference between that effector and palm-like structure 91' and structures supported thereby such as effectors 110' A, 110' B, 110' C, and by the maximum excursions of output shaft 156' and output body 161' of the linear actuators 154' and 159' from the bases thereof. Practically, again, however, the angular range limits for gripping effector base 158' will be established by operating controls provided in the controller with respect to actuators 154' and 159' to limit the excursions of output shaft 156' and output body 161' thereof with respect to the corresponding base for the conditions expected to be encountered by gripping effector base 158' during operation thereof.

The far end of the of the long part of the cylindrical shaft portion in gripping effector base 158' fits into a sleeve portion of an actuator holder in gripping effector base 158' which has an opening therein at the end of this sleeve portion past the end of the cylindrical shaft portion. Through this opening a pin, 164', is provided to rotatably connect a first gripping extension, 165', to gripping effector base 158'. A clevis-like end of first gripping extension 165' has two extensions between which the far end of the sleeve part of actuator holder in gripping effector base 158' is positioned to be held by pivot pin 164' extending through the opening therein and through the two extensions of clevis-like end of the extension.

A linear actuator, 166', has a base end, 167', thereof (which may contain a force sensor) affixed in an partial ring end of a holding bracket at the opposite end of the actuator holder in gripping effector base 158'. This holding bracket in actuator holder is formed by two arms extending from the sleeve portion thereof along much of the long part of the cylindrical shaft portion to the partial ring which is formed following a semicircular path extending from these two arms outwardly away from the cylindrical shaft portion. The end of a moveable outer body shell, 168', of actuator 166' is rotatably connected between a pair of extensions forming a yolk in first gripping extension 165' by further pair of pivot pins, 169'. Extensions and retractions of moveable outer body 168' force first gripping extension 165' to rotate forward and backward about pivot pin 164' with respect to gripping effector base 158' to permit further circumscription of an object between them and one or more of the aligned effector based open chains in gripping that object. Here too, wiring, not shown, connects linear actuator 166' to the controller for directing the operation thereof.

A second gripping extension, 170', has a portion thereof rotatably connected to first gripping extension 165' between two spaced apart, extended portions thereof forming a yoke by a pin, 171', fixed in these extended portions at the end of the first gripping extension opposite the clevis-like end of first gripping extension 166' connected to gripping effector base 158'. Pin 171' also has a gear centrally mounted thereon. This gear is engaged with gears not seen in first gripping extension 165' forcing second gripping extension 170' to rotate with respect to first gripping extension 165' when the latter is rotated with respect to gripping effector base 158', and again adds to the capture arc formed by the extent of them as an open linkage chain.

Again, as shown in FIG. 10B, linear actuators **154'**, **159'** and **166'** of FIGS. **5**, **10A**, **11**, **12** and **13** can have alternative linear actuators like linear actuator **115'''** A substituted therefor. Thus, linear actuators **154'''**, **159'''** and **166'''** are shown in FIG. 10B replacing linear actuators **154'**, **159'** and **166'** of FIGS. **5**, **10A**, **11**, **12** and **13**.

Returning to robot **40** of FIG. **2**, a manipulator, **10C**, like manipulator **10** of FIG. **1**, supports the base of "tee" structure **41** in robot **40** in having this structure mounted on manipulable support **32C** thereof. Mounting arrangement **11C**, having one end thereof connected to base support **12C** of manipulator **10C**, has the other end connected to a rounded corner, triangular shaped surface of a triangular shaped support plate structure, **180**, extending between two such triangular shaped surfaces, which thus supports the upper torsolike portion of robot **40**. Linear actuators **15C** and **16C** are mounted on support pedestals **14C** on mounting arrangement **11C** and connected to the corresponding lower pivoting links which can cause manipulable support **32C** of manipulator **10C**, supporting "tee" **41** and the structures connected thereto including any head-like structure provided, to move to simulate selected bending motion of the human upper torso under direction of the controller. Supplementing linear actuators **15C** and **16C** are two further linear actuators, **35C** and **37C**, which are mounted on support pedestals **14C** on mounting arrangement **11C** and connected to the corresponding lower pivoting links just as are linear actuators **15C** and **16C**. These added linear actuators can, in addition to providing further force and stability, be operated antagonistically with the other linear actuators to thereby reduce backlash in the motion of manipulator **10C**, and they allow manipulator **10C** to more precisely position the upper torso-like portion of robot **40** under direction of the system controller after the leg-like portions thereof (to be described below) have been used to coarsely position that robot. Alternatively, additions **35C** and **37C** can, instead of being linear actuators, be shock absorbers to damp impulsive forces on manipulator **10C**.

Triangular shaped support plate structure **180** has an angled bracket plate, **181**, with a first plate portion fastened to a side of structure **180** extending perpendicularly to the triangular surface supporting mounting arrangement **11C** across from a corner of that surface. A second plate portion of angle bracket plate **181** is more or less of a rectangular shape and bent from the first plate portion away from structure **180**. A first side of second plate portion of angle bracket **181** approximately perpendicular to the bend in that plate, and on the left in viewing FIG. **2**, has a manipulator, **10D**, like manipulator **10** of FIG. **1**, useful for simulating a human right hip, mounted thereto parallel to the long axis of mounting arrangement **11D** of manipulator **10D** between its connection to base support **12D** (unseen in FIG. **2**) and support pedestals **14D** thereon. Linear actuators **35D** and **37D** (connected to lower pivoting links **20"** D and **20'"** D rather than to lower pivoting links **20D** and **20'** D in the manner of linear actuators **16** and **15** in FIG. **1** being connected to lower pivoting links **20** and **20'** there) are mounted on support pedestals **14D** on mounting arrangement **11D** and connected to the corresponding lower pivoting links which can cause manipulable support **32D** of manipulator **10D** to move to simulate selected right human hip motion under direction of the controller.

Manipulable support **32D** is connected to a bent upper leg bar, **182**, which has at its opposite end a yoke, **183**, in which a lower leg bar, **184**, is rotatably connected by a pair of pin-like bosses, **185**, each extending through a yoke arm opening to be affixed in the sides of the upper leg bar yoke

thereby forming a single degree of freedom joint, **186**, simulating a human knee. A linear actuator, **187**, is connected between upper leg bar **182** and lower leg bar **184** to operate that joint by causing lower leg bar **184** to selectively rotate in yoke **183** about pin-like bosses **185**. A motor and a rotational joint arrangement contained within upper leg bar **182** allows it to be rotated over an angular range with respect to manipulator **10D**. A two degree of freedom joint, **190**, simulating a human ankle, to which a foot-like structure, **191**, is attached, is mounted on the end of lower leg bar **184**, and a motor and a rotational joint arrangement contained within lower leg bar **184** allows two degree of freedom joint **190** together with foot-like structure **191** to be rotated over an angular range with respect to lower leg bar **184**.

Similarly, a second side of second plate portion of angle bracket **181** at a shallow acute angle with, but primarily parallel to, the first side to also be approximately perpendicular to the bend in that plate, and on the right in viewing FIG. **2**, has a manipulator, **10E**, like manipulator **10** of FIG. **1**, useful for simulating a human left hip, mounted thereto parallel to the long axis of mounting arrangement **11E** of manipulator **10E** between its connection to base support **12E** and support pedestals **14E** thereon (not seen in FIG. **2**). Linear actuators **15E** and **16E** (not all seen in FIG. **2**) are mounted on support pedestals **14E** on mounting arrangement **11E** and connected to the corresponding lower pivoting links which can cause manipulable support **32E** of manipulator **10E** to move to simulate selected right human hip motion under direction of the controller.

Manipulable support **32E** is connected to a bent upper leg bar, **182'**, which has at its opposite end a yoke, **183'**, in which a lower leg bar, **184'**, is rotatably connected by a pair of pin-like bosses, **185'**, each extending through a yoke arm opening to be affixed in the sides of the upper leg bar yoke thereby forming a single degree of freedom joint, **186'**, simulating a human knee. A linear actuator, **187'**, is connected between upper leg bar **182'** and lower leg bar **184'** to operate that joint by causing lower leg bar **184'** to selectively rotate in yoke **183'** about pin-like bosses **185'**. A two degree of freedom joint, **190'**, simulating a human ankle, to which a foot-like structure, **191'**, is attached, is mounted on the end of lower leg bar **184'**, and a motor and a rotational joint arrangement contained within lower leg bar **184'** allows two degree of freedom joint **190'** together with foot-like structure **191'** to be rotated over an angular range with respect to lower leg bar **184'**.

Two degree of freedom joints **190** and **190'** are shown to be identical in FIG. **2**, and shown in greater detail in FIG. **15**. Joint **190** will be described with structures in joint **190'** mounted on the end of lower leg bar **184'** identical to those in joint **190** mounted on the end of lower leg bar **184** having the same numerical designations there as they do in joint **190** but with a following prime mark.

Joint **190** has, as seen in FIGS. **2** and **15**, a flared housing, **192**, formed as a truncated cone shell portion having its small diameter end fastened about lower leg bar **184** and its large diameter end joined to a truncated cylindrical shell portion which has an open end at the end thereof opposite to its end joined to the truncated cone shell portion. A circular joint housing ring, unseen in FIGS. **2** and **15**, also formed as a truncated cylindrical shell, is mounted on the inner periphery of the cylindrical shell portion of housing **192** inward from its open end. This housing ring has the shell thereof extended into four bosses parallel to the axis of radial symmetry at four locations 90° apart on this ring with each boss having an opening therein in which a bushing is provided. A pair of openings, unseen in FIGS. **2** and **15**, is

provided in the truncated cylindrical shell of housing **192** each across from, and axially aligned with, a corresponding one of two adjacent ones of these ring boss openings.

A shaft, **193**, formed as a truncated cylinder, having a pulley, **194**, affixed to an outer end thereof, extends from pulley **194** through one of the pair of housing truncated cylindrical shell openings and through the bushing in the ring boss opening across therefrom to be joined at its end to an output carrier, **195**, extending between this ring boss opening and the ring boss opening opposite thereto on the other side of the ring housing. A shaft, **196**, formed as a truncated cylinder, is affixed to the opposite end of output carrier **195** from the end thereof affixed to shaft **193** which extends into the bushing in this opposite side ring boss opening so that output carrier **195** is rotatably supported by the housing ring in opposite side ring boss openings thereof on shafts **193** and **196** to have an axis of rotation which includes the axes of radial symmetry of these shafts.

Output carrier **195** is formed as a closed loop metal strap with two rectangular plate long sides joined at the ends thereof by two curved plate short sides therebetween to which shafts **193** and **196** are affixed, thus leaving an open interior for the carrier between the long sides and the short sides accessible from both open sides of the closed strap loop. An output bar, **197**, formed as a truncated cylinder, has one end thereof positioned within the interior of the closed strap loop of output carrier **195** and rotatably connected thereto by a pin, **198**, extending through this output shaft and through bushings in each of two openings each of which is centered in one of the long sides of the closed strap loop of output carrier **195**. The other end of output bar **197** is affixed to foot-like structure **191**.

A further shaft, **199**, formed as a truncated cylinder, having a pulley, **200**, affixed to an outer end thereof, extends from pulley **199** through one of the pair of housing truncated cylindrical shell openings and through the bushing in the ring boss opening across therefrom to be joined at its end to a joined double bail, **201**, extending between this ring boss opening and the ring boss opening opposite thereto on the other side of the ring housing. A shaft, unseen in FIGS. 2 and **15**, formed as a truncated cylinder, is affixed to the opposite end of joined double bail **201** from the end thereof affixed to shaft **199** which extends into the bushing in this opposite side ring boss opening so that output carrier joined double bail **201** is rotatably supported by the housing ring in opposite side ring boss openings thereof on shaft **199** and the unseen shaft on its opposite side to have an axis of rotation which includes the axes of radial symmetry of these shafts.

Joined double bail **201** is formed as two spaced apart, parallelly oriented half rings that a rejoined to one another at the half ring ends by two curved plate short sides therebetween to which shafts **199** and the unseen attached shaft are affixed, thus leaving an open interior between the half rings and the short sides. The end of output bar **197** affixed to foot-like structure **191** is positioned to extend through this joined double bail interior opening in extending between its rotatable connection to output carrier **195** and its point of attachment to foot-like structure **191**. A pair of relatively low friction sliding rings, **202**, are positioned about output bar **197** to be between that output bar and the half rings of joined double bail **201** to permit these rings to guide motion of output bar **197** in its sliding back and forth therebetween. Thus, the rotation of pulley **194** and shaft **193** to rotate output carrier **195** results in rotation of output bar **197** perpendicular to the axis of rotation of output carrier **195** for any angle of joined double bail **201** set by the rotation of joined double bail **201** resulting from the rotation of pulley **200** and shaft **199**.

A truncated cylindrical shell shaped motor housing, **203**, is affixed in and through leg bar **184** with its axis of radial symmetry oriented perpendicular to the long axis of leg bar **184** and parallel to the axis of radial symmetry of shaft **199**. Motor housing **203** has the end thereof on the side of leg bar **184** on which pulley **200** is positioned open to receive an electrical motor therein with the other end typically closed.

Another truncated cylindrical shell shaped motor housing, **204**, is affixed in and through leg bar **184** closer to foot-like structure **191** with its axis of radial symmetry oriented perpendicular to that of motor housing **203** and to the long axis of leg bar **184**, but parallel to the axis of radial symmetry of shaft **193**. Motor housing **204** has the end thereof on the side of leg bar **184** on which pulley **194** is positioned open to receive an electrical motor therein, and typically, again, the other end of motor housing **204** is closed.

Leg bar **184** typically has an opening extending therethrough to allow control wiring to be installed. Motor housing **203**, in addition to having some of such wiring terminate there for the motor to be provided therein, also has sufficient space therein to allow such wiring to pass from leg bar **184** to reach motor housing **204** for the motor to be provided there. Additional wiring, or other facilitating means, may also be passed through such openings and spaces if needed.

Rotation of joined double bail **201** about its axis of rotation is driven by an electrical motor, unseen in FIGS. **2** and **15**, provided in motor housing **203**. This motor has an output shaft connected to a speed reduction gearbox, unseen in FIGS. 2 and 15, having an output shaft, **205**, affixed to a drive pulley, **206**. A drive belt, **207**, couples drive pulley **206** to driven pulley **200** to enable the motor in housing **203** to rotate pulley **200** and shaft **199**, and so joined double bail **201**, over a selected angular range in the associated possible range of rotation under direction of the control system connected to the motor in housing **203** by wires provided as described above.

Similarly, rotation of output carrier **195** about its axis of rotation is driven by an electrical motor, unseen in FIGS. **2** and **15**, provided in motor housing **204**. This motor has an output shaft connected to a speed reduction gearbox, unseen in FIGS. 2 and 15, having an output shaft, **208**, affixed to a drive pulley, **209**. A drive belt, **210**, couples drive pulley **209** to driven pulley 194 to enable the motor in motor housing **204** to rotate driven pulley **194** and shaft **193**, and so output carrier **195** over a selected angular range in the associated possible range of rotation under direction of the control system connected to the motor in housing **204** by wires provided as described above.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. A controlled relative motion system having first and second support structures with said first support structure having a first support offset structure extending along a first axis and said second support structure having a second support offset structure extending along a second axis, said system comprising:

an intermediate joint having a base member and a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface,

said intermediate joint base being affixed to an interior end of a selected one of said first and second support offset structures with said output carrier affixed to an interior end of that one remaining;

a first support joint having a base member supported by and affixed with respect to said first support offset structure at an exterior end thereof opposite said interior end thereof along said first axis and further having a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface; and

a second support joint having a base member supported by and affixed with respect to said second support offset structure at an exterior end thereof opposite said interior end thereof along said second axis and further having a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface.

2. The system of claim 1 further comprising having said first support joint supported by and affixed with respect to said first support offset structure at an exterior end thereof through a first support holder structure affixed to said first support offset structure at said exterior end thereof at a location in said first support holder structure intersected by said first axis that is intermediate to two spaced apart holders in said first support holder structure to one of which said first support joint base member is affixed, and with a base member of a first supplemental support joint affixed to that remaining holder, said first supplemental support joint further comprising a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface.

3. The system of claim 1 further comprising having said second support joint supported by and affixed with respect to said second support offset structure at an exterior end thereof through a second support holder structure affixed to said second support offset structure at said exterior end thereof at a location in said second support holder structure intersected by said second axis that is intermediate to two spaced apart holders in said second support holder structure to one of which said second support joint base member is affixed, and with a base member of a second supplemental support joint affixed to that remaining holder, said second supplemental support joint further comprising a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface.

4. The system of claim 2 wherein said first support joint, with said output carrier of said first support joint controlled position member maximally spaced apart from said first support joint base member, defines a first support joint extension axis through said first support joint base member and said first support joint output carrier, and wherein said first supplemental support joint, with said output carrier of said first supplemental support joint controlled position member maximally spaced apart from said first supplemental support joint base member, defines a first supplemental support joint extension axis through said first supplemental support joint base member and said first supplemental support joint output carrier, said first support joint extension axis and said first supplemental support joint extension axes being nonparallel.

5. The system of claim 2 further comprising having said second support joint supported by and affixed with respect to

said second support offset structure at an exterior end thereof through a second support holder structure affixed to said second support offset structure at said exterior end thereof at a location in said second support holder structure intersected by said second axis that is intermediate to two spaced apart holders in said second support holder structure to one of which said second support joint base member is affixed, and with a base member of a second supplemental support joint affixed to that remaining holder, said second supplemental support joint further comprising a controlled position member that has an output carrier which can be angularly positioned with respect to said base member anywhere over a selected spatial surface.

6. The system of claim 3 wherein said second support joint, with said output carrier of said second support joint controlled position member maximally spaced apart from said second support joint base member, defines a second support joint extension axis through said second support joint base member and said second support joint output carrier, and wherein said second supplemental support joint, with said output carrier of said second supplemental support joint controlled position member maximally spaced apart from said second supplemental support joint base member, defines a second supplemental support joint extension axis through said second supplemental support joint base member and said second supplemental support joint output carrier, said second support joint extension axis and said second supplemental support joint extension axes at least partly extending along said second axis.

7. The system of claim 5 wherein said intermediate joint, said first support joint, said first supplemental support joint, said second support joint and said second supplemental support joint further comprise at least one pivot holder comprising at least one member, an initial plurality of pivoting links each rotatably connected at one end thereof to a said pivot holder and rotatably connected at an opposite end thereof to said base member thereof and a subsequent plurality of pivoting links each rotatably connected at one end thereof to a said pivot holder and rotatably connected at an opposite end thereof to said output carrier thereof.

8. The system of claim 7 wherein each one of several pluralities of force imparting members is coupled to a corresponding one of said intermediate joint, said first support joint, said first supplemental support joint, said second support joint and said second supplemental support joint with each said force imparting means in a said plurality thereof provided for said corresponding joint being coupled to a an initial pivot link in said plurality thereof for said corresponding joint so as to be able to impart a force thereto to cause at least one of said initial plurality of pivoting links for said corresponding joint to rotate about an axis therethrough.

9. The system of claim 8 wherein said first support joint, said first supplemental support joint, said second support joint and said second supplemental support joint have said output carriers thereof each coupled through an extension member to a base member of a corresponding further joint having a controlled position member with an output carrier which can be selectively positioned with respect to said base member thereof, and with said extension member being rotatable with respect to that output carrier coupled thereto.

10. The system of claim 9 further comprising at least one of said further joints has said output carrier thereof coupled through a subsequent extension member to a base member of a corresponding terminating joint having a pair of slotted members rotatably coupled to said subsequent extension to each be capable of rotating about a corresponding one of a

pair of axes substantially perpendicular to one another with a slot in each of said slotted members extending along said corresponding rotation axis thereof, said terminating joint further having an output carrier extending at least in part through said slot in each of said slotted members and a pair of force imparting means each coupled to a corresponding one of said slotted members to be capable of causing rotation thereof about said rotation axis corresponding thereto.

11. An articulated manipulating system for mounting on a base in a robotic manipulator and capable of engaging selected objects, said system comprising:

a subbase rotatably mounted on said base to have a single subbase rotation axis therethrough;

a first linear actuator coupled at one end thereof to said base and coupled at an opposite end thereof to said subbase to be capable of rotating said subbase about said subbase rotation axis;

a first effector base rotatably connected to said subbase to have a first effector rotation axis;

a second linear actuator coupled at one end thereof to said subbase and coupled at an opposite end thereof to said first effector base to be capable of rotating said first effector base about said first effector rotation axis.

12. The system of claim **10** further comprising a shackle having a pair of arms spaced apart by a recess space which arms are joined in a joining bar on one side of said recess space, an effector base rotatably mounted at a pivot location thereof to and between said spaced apart arms of the shackle so as to leave a recess space between an end of that said effector base rotatably mounted to said shackle and said joining bar thereof, a pedestal affixed to said base relatively near to where said subbase is rotatably mounted on said base and having said joining bar of said shackle rotatably coupled thereto, a gripping extension rotatably coupled to said effector base at an extension coupling location thereof spaced apart from said pivot location thereof, an extension linear actuator positioned adjacent to said effector base and coupled at one end thereof so as to have that end positioned at least in part in said recess space of said shackle with that remaining end of said linear actuator rotatably coupled to that said gripping extension, and a pair of effector linear actuators each having an end thereof connected to said base at corresponding base connection locations thereon, and each having that opposite end thereof rotatably connected to a said effector base at corresponding effector connection locations thereon so that any substantial differentials in movement of these actuators cause corresponding substantial motions of said effector base towards a corresponding one of said base connection locations and so that substantial common movements of these actuators causes substantial motions of said effector base toward or away from both of said base connection locations.

13. The system of claim **12** wherein said extension linear actuator has said one end thereof coupled to said effector base.

14. An articulated manipulating system for mounting on a base in a robotic manipulator and capable of engaging selected objects, said system comprising:

a plurality of shackles each having a pair of arms spaced apart by a recess space with said arms being joined in a joining structure on one side of said recess space;

a plurality of effector bases each rotatably mounted at a pivot location thereof to and between said separated arms of a corresponding shackle so as to leave a recess space between an end of that said effector base rotatably mounted to said shackle and said joining structure thereof;

a fixed pedestal affixed to said base and having said joining structure of a corresponding one of said plurality of shackles rotatably coupled thereto;

a moveable pedestal rotatably connected to said base and having said joining structure of a corresponding one of said plurality of shackles rotatably coupled thereto; and

a pedestal linear actuator coupled at one end thereof to said base and coupled at an opposite end thereof to said moveable pedestal to be capable of rotating said moveable pedestal with respect to said base.

15. The system of claim **14** further comprising a plurality of gripping extensions each rotatably coupled to a corresponding one of said plurality of effector bases at an extension coupling location thereof spaced apart from said pivot location thereof, and a plurality of extension linear actuators each positioned adjacent to a corresponding one of said plurality of effector bases and each coupled at one end thereof so as to have that end positioned at least in part in said recess space of said shackle to which said corresponding effector base is rotatably coupled with that remaining end of said linear actuator rotatably coupled to that said gripping extension rotatably coupled to said corresponding effector base.

16. The system of claim **14** further comprising a pair of effector linear actuators each having an end thereof connected to said base at corresponding base connection locations thereon, and each having that opposite end thereof rotatably connected to a corresponding common one of said plurality of effector bases at corresponding effector connection locations thereon separated from said extension coupling location thereof by said pivot location so that any substantial differentials in movement of these actuators cause corresponding substantial motions of said corresponding effector base towards a corresponding one of said base connection locations and so that substantial common movements of these actuators causes substantial motions of said effector base toward or away from both of said base connection locations.

17. The system of claim **15** wherein each of said extension linear actuators in said plurality thereof has said one end thereof coupled to said corresponding effector base.

18. The system of claim **15** further comprising a pair of effector linear actuators each having an end thereof connected to said base at corresponding base connection locations thereon, and each having that opposite end thereof rotatably connected to a corresponding common one of said plurality of effector bases at corresponding effector connection locations thereon separated from said extension coupling location thereof by said pivot location so that any substantial differentials in movement of these actuators cause corresponding substantial motions of said corresponding effector base towards a corresponding one of said base connection locations and so that substantial common movements of these actuators causes substantial motions of said effector base toward or away from both of said base connection locations.

19. The system of claim **16** wherein one of said pair of effector linear actuators has said end thereof connected to said base so as to face a portion of that said opposite end of that remaining one of said pair of effector linear actuators in said pair of effector linear actuators each having that said opposite end thereof rotatably connected to said corresponding common one of said plurality of effector bases at corresponding effector connection locations thereon.

20. A controlled relative motion system having a base mounted in a robotic manipulator, said system comprising:

an extended open interior member being rotatably coupled to said base to be capable of rotating about a

corresponding interior member rotation axis along which a pair of spaced apart interior member sides extend so as to have an extended space therebetween, said extended open interior member being rotatably coupled to said base at an end thereof joining said interior member sides at one end of said extended space by a first shaft coupled thereto and being rotatably coupled to said base at an opposite end thereof also joining said interior member sides at an opposite end of said extended space by a second shaft coupled thereto;

an output carrier having a pair of output carrier sides spaced apart by a recess space with said output carrier sides being joined in a joining structure on one side of said recess space, said output carrier being positioned to have said extended open interior member in said recess space with said output carrier sides at least in part extending substantially parallel to said interior member sides and to being rotatably coupled to said extended open interior member to be capable of rotating about a corresponding output carrier rotation axis substantially perpendicular to said interior member rotation axis, said output carrier being rotatably coupled to said extended open interior member by a follower shaft affixed to said output carrier and rotatably coupled to said extended open interior member;

an interior member first bevel gear located in said extended space and affixed to said first shaft;

an output carrier first bevel gear located in said extended space and affixed to said follower shaft to be engaged with said interior member first bevel gear; and

a plurality of force imparting means mounted in said base with each of said first and second shafts being rotatably coupled to a corresponding one of said force imparting means in said plurality thereof.

21. The system of claim **18** wherein said second shaft is fixedly coupled to said extended open interior member at said opposite end thereof, and said follower shaft is rotatably coupled to said extended open interior member by passing through and being rotatably coupled to both said interior member sides and is affixed to both said output carrier sides.

22. The system of claim **18** wherein said second shaft is rotatably coupled to said extended open interior member at said opposite end thereof and further comprising said output carrier being also rotatably coupled to said extended open interior member by a gear shaft rotatably coupled to both said output carrier and to said extended open interior member, an interior member second bevel gear located in said extended space and affixed to said second shaft to be engaged with said output carrier first bevel gear, and an output carrier second bevel gear located in said extended space and affixed to said gear shaft to be engaged with said interior member first and second bevel gears.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,658,962 B1
DATED : December 9, 2003
INVENTOR(S) : Mark E. Rosheim

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1,
Lines 19, 57, 58, 60 and 63, delete "of ten" and insert -- often --

Column 4,
Lines 1, 4 and 54, delete "devises" and insert -- clevises --

Column 6,
Line 19, delete "of ten" and insert -- often --

Column 14,
Line 47, after "106' C" insert -- , --
Line 51, delete "devises" and insert -- clevises --

Column 15,
Line 14, delete "devises" and insert -- clevises --

Column 16,
Line 1, delete "116' A" and insert -- 116''' A --

Column 17,
Line 59, delete "115" C and 116' C, and 115' D" and insert -- 115''' C and 116''' C, and 115''' D --

Column 23,
Line 49, delete "a rejoined", insert -- are rejoined --

Signed and Sealed this

Twenty-fourth Day of February, 2004

Jon W. Dudas

JON W. DUDAS
Acting Director of the United States Patent and Trademark Office

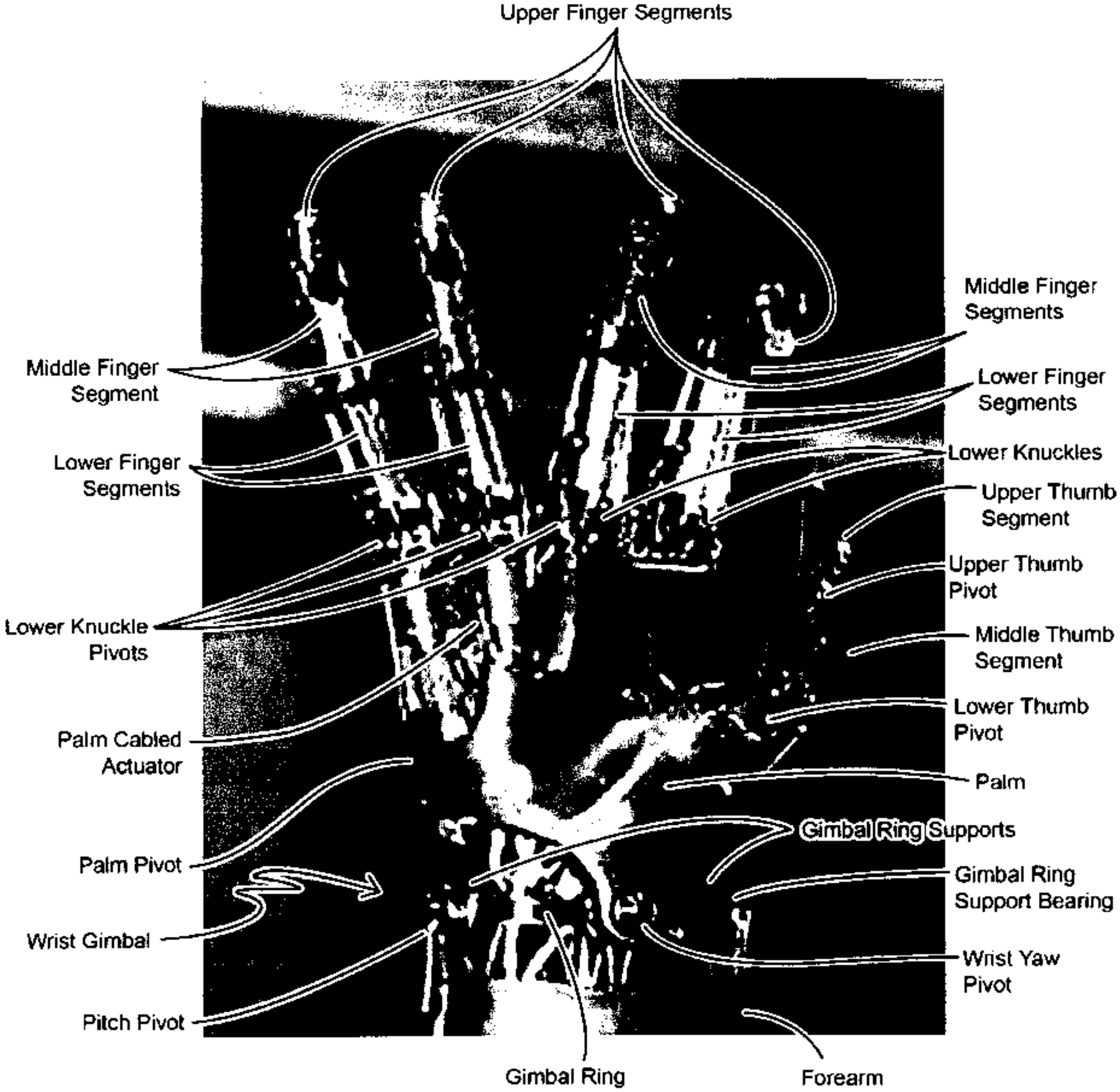

Exhibit 3. Robonaut 1 Hand, NASA subcontractor photograph.

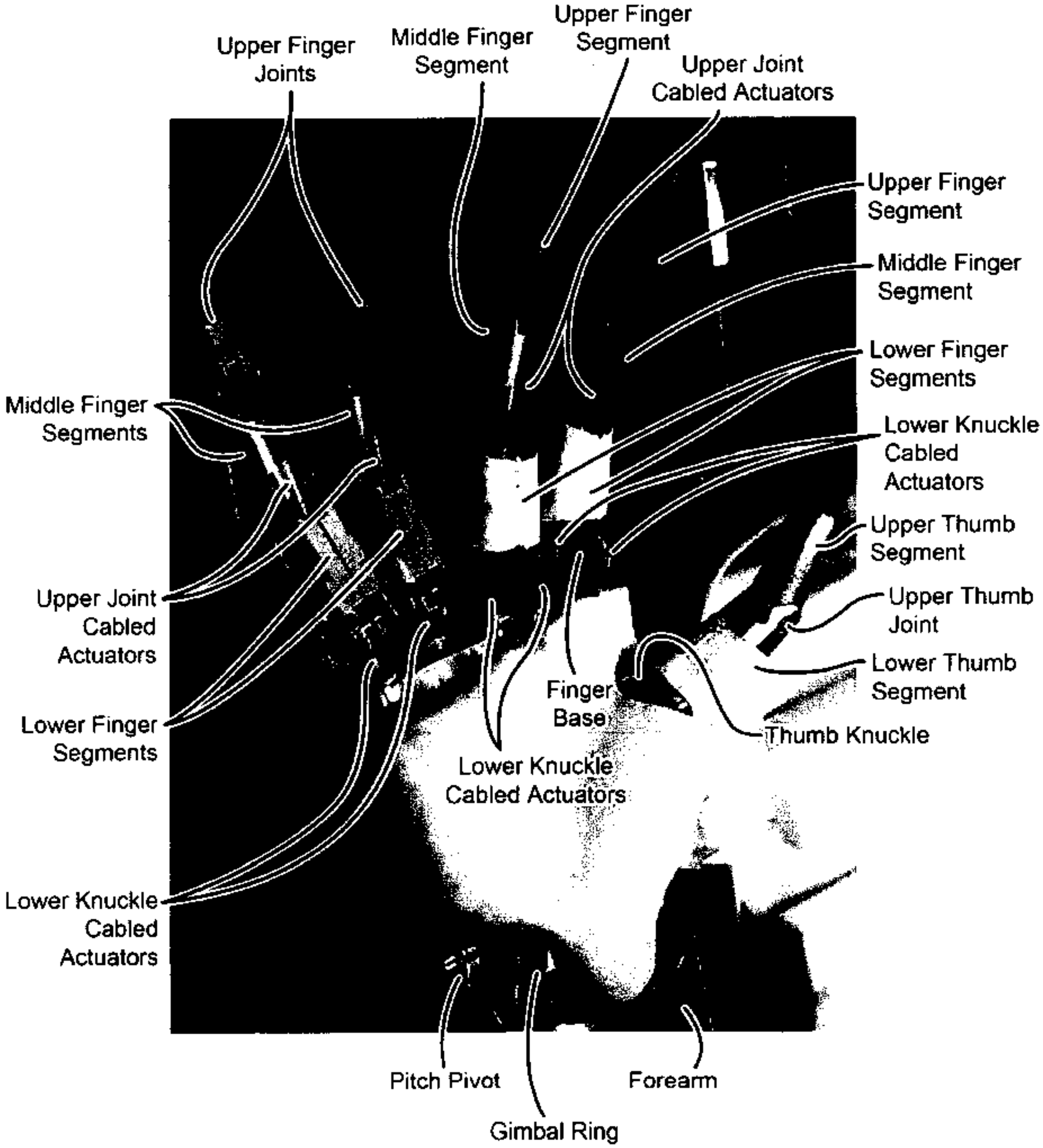

Exhibit 4. Robonaut 1 Hand, NASA visitor photograph.

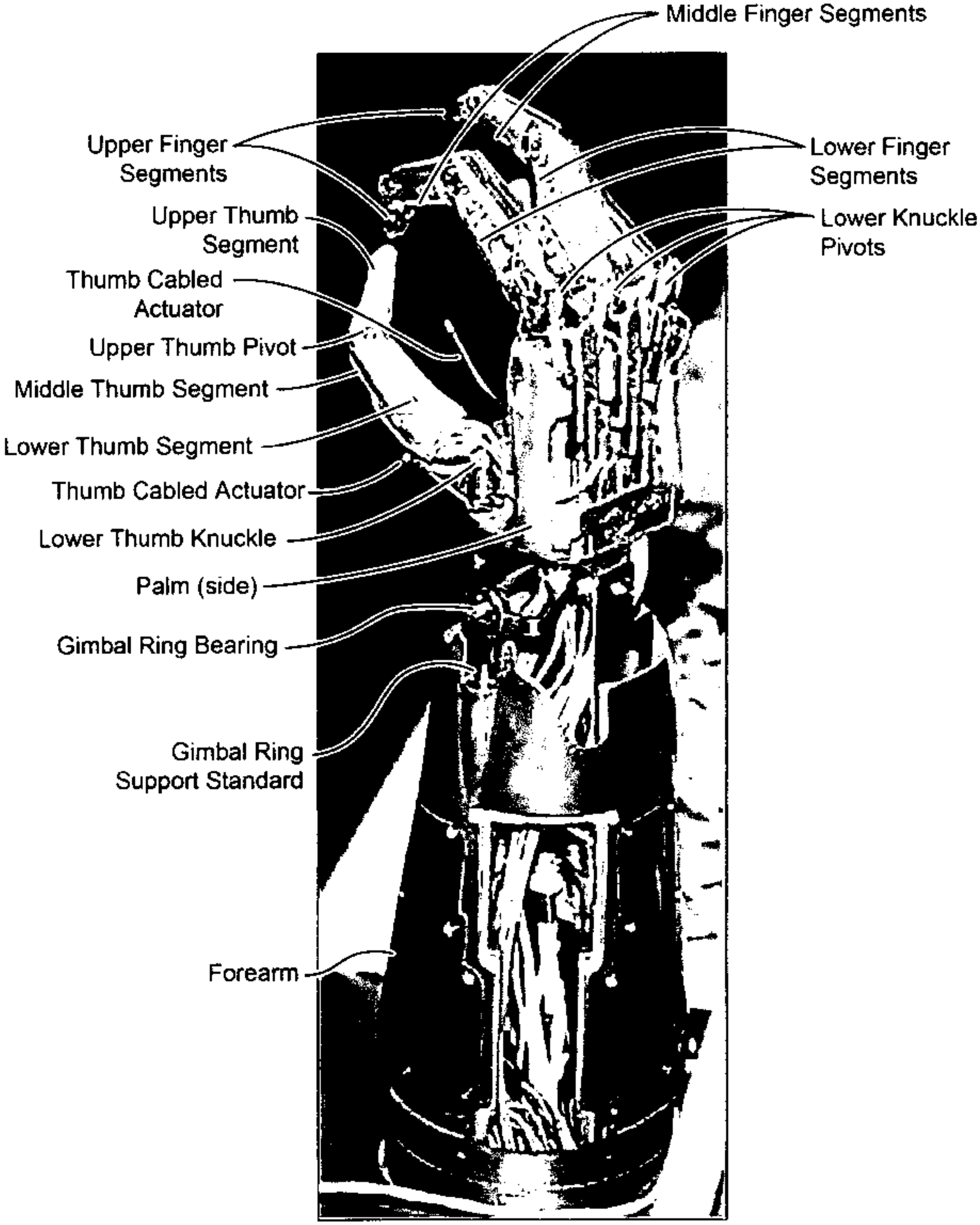

Exhibit 5. Robonaut 1 Hand, NASA subcontractor photograph.

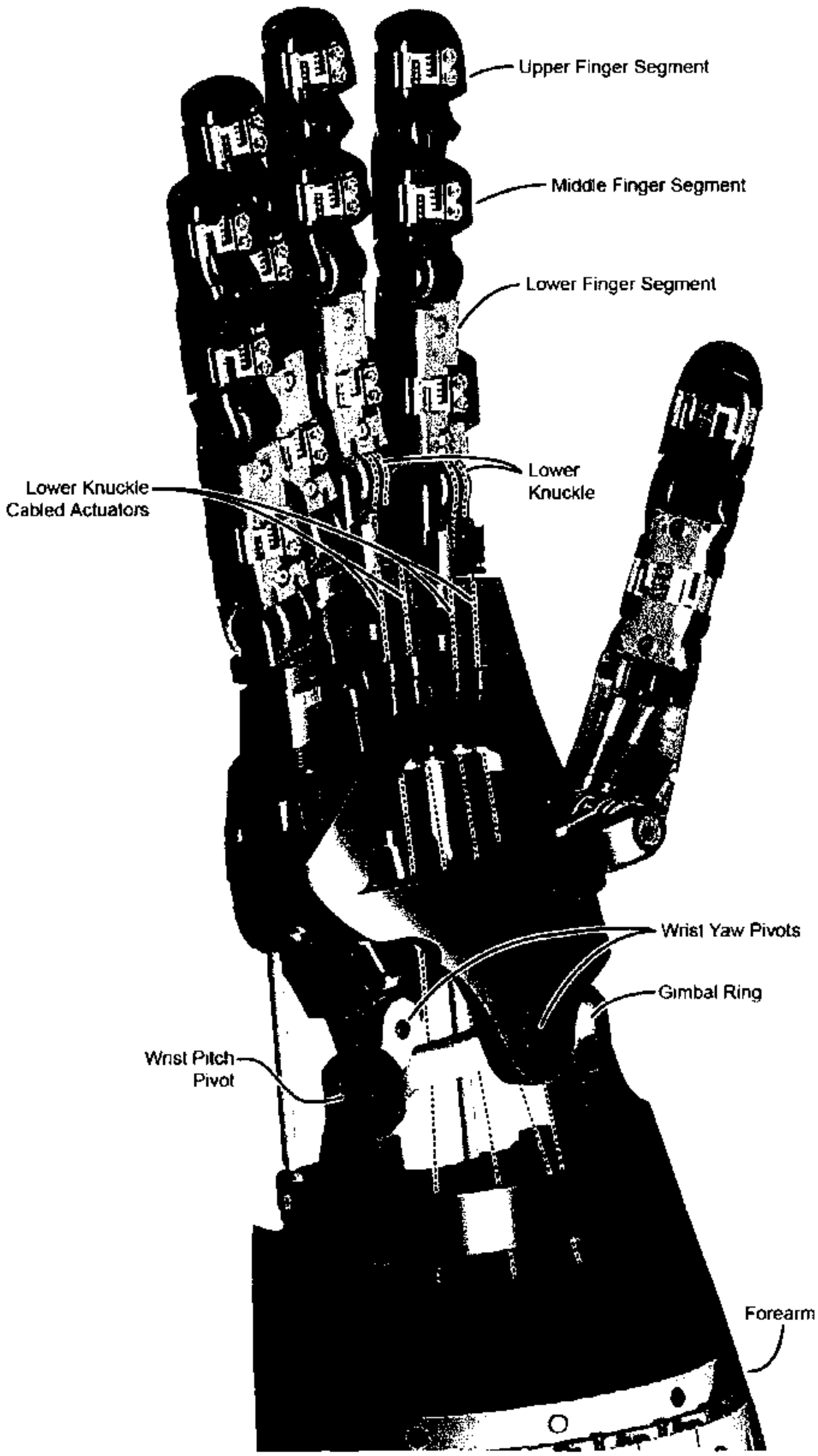

Exhibit 6. Robonaut 2 Hand, NASA slideshow.

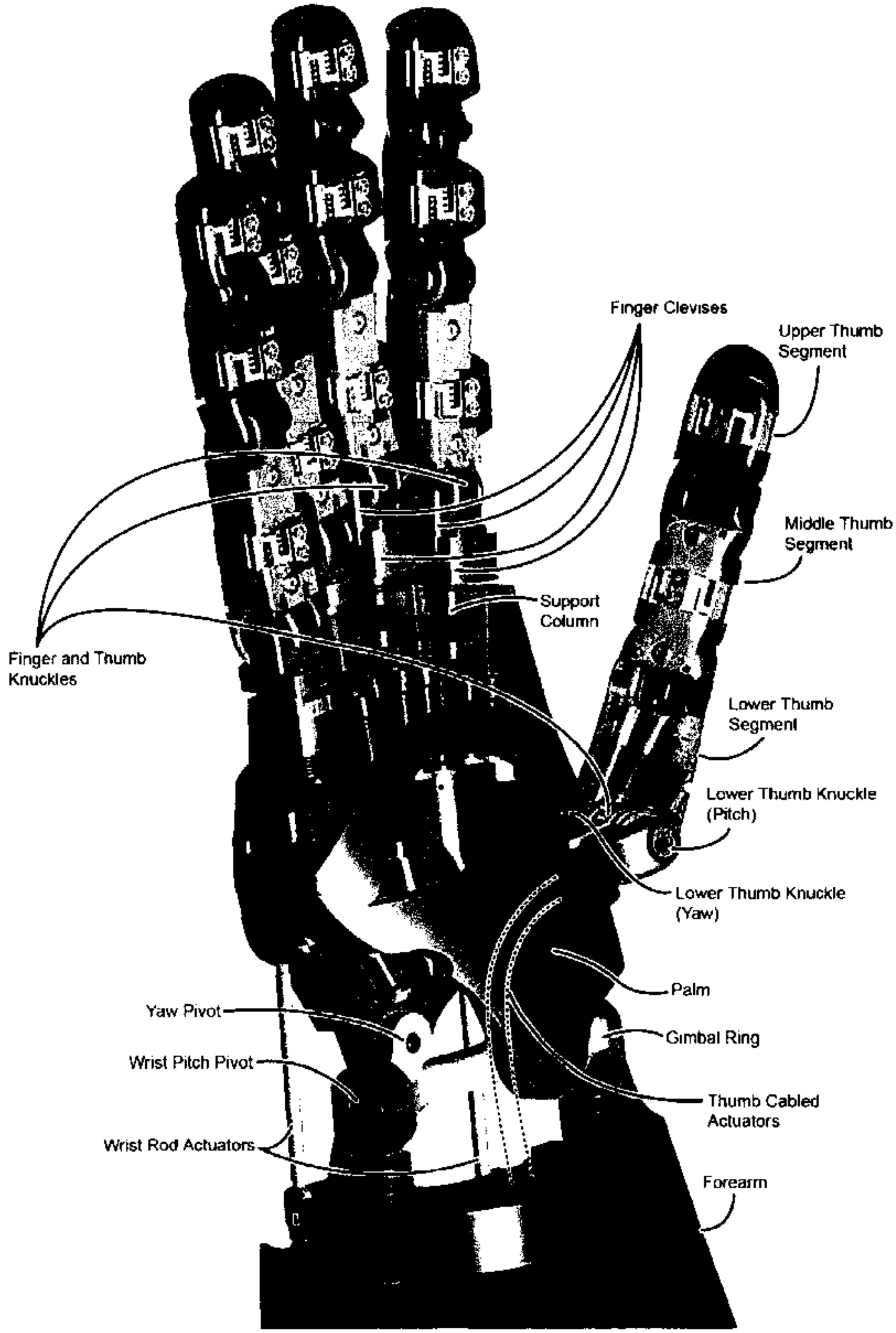

Exhibit 7. Robonaut 2 Hand, NASA slideshow.

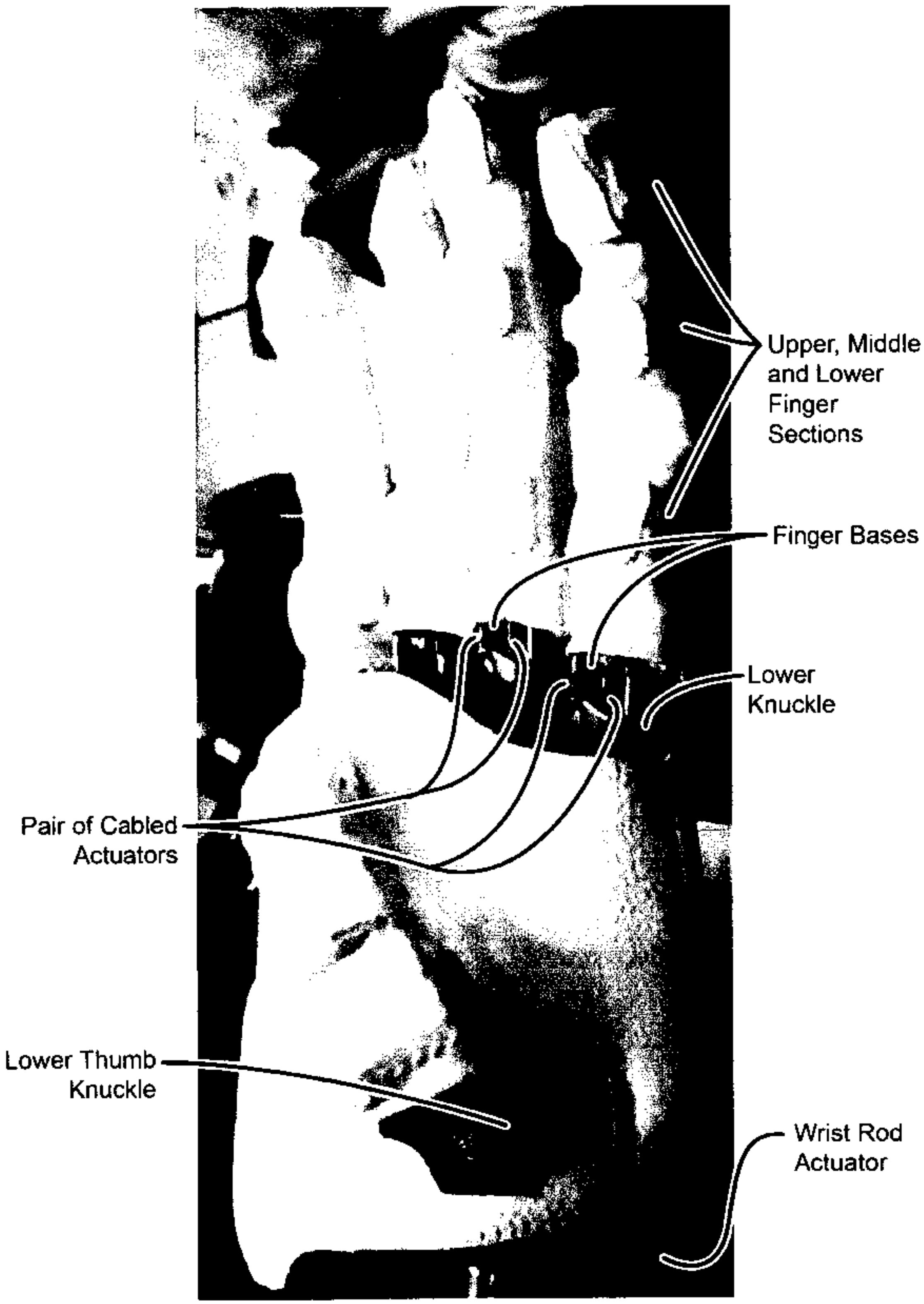

Exhibit 8. Robonaut 2 Hand, NASA slideshow.